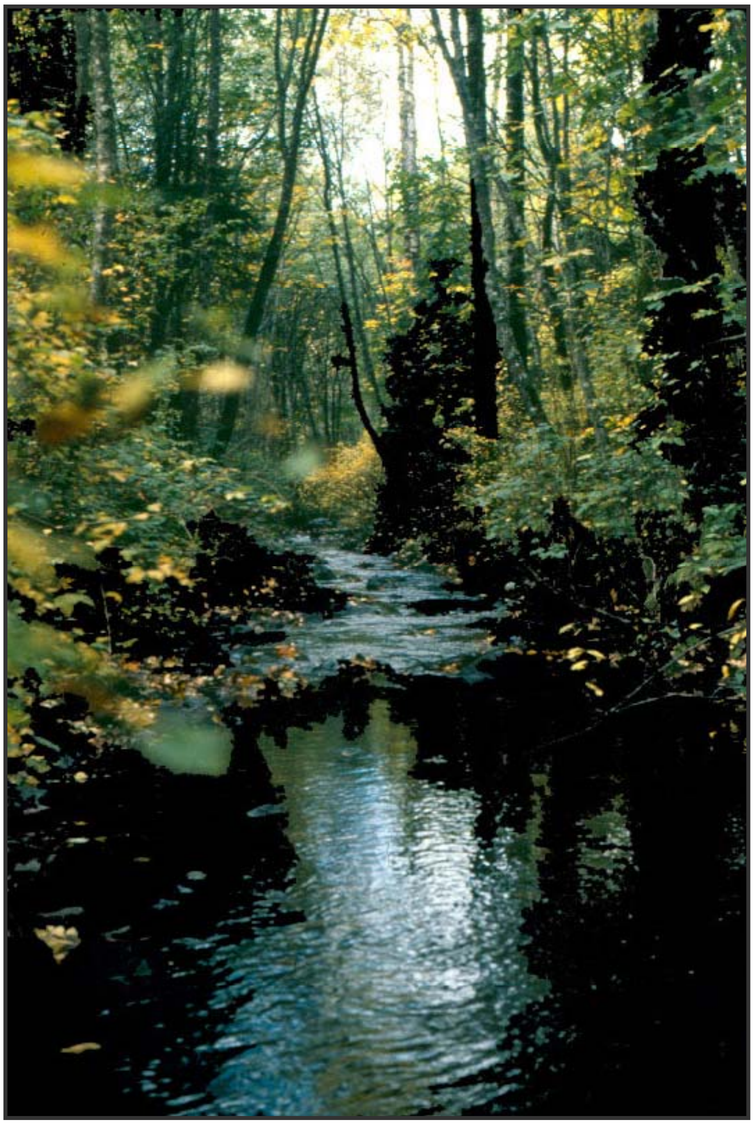
Development of Hydrological and Biological Indicators of Flow Alteration in Puget Sound Lowland Streams



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King County

Department of Natural Resources and Parks

Development of Hydrological and Biological Indicators of Flow Alteration in Puget Sound Lowland Streams

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Table of Contents

Figures

Tables

Appendices

EXECUTIVE SUMMARY

The Normative Flow Project (NFP) began in 2001 with the goal of developing an ecologically-based flow assessment method that could be used by King County resource managers to (a) evaluate the effects of past, present, and future water and land management actions on the flow regimes of streams and rivers; (b) evaluate the effects of altered flow regimes on the physical and biological conditions in rivers and streams; and (c) guide management actions to reduce these effects through mitigation, protection, and restoration of flow regimes that support ecosystem integrity and salmon conservation.

Because of the difficulty in measuring many ecosystem attributes directly, especially those with long time frames and large spatial scales, the preferred methodological approach is indicator-based, relying on surrogates for ecosystem function found in the hydrologic and biological characteristics of small streams. The first task (reported here) was to derive a set of hydrologic and biological metrics (from existing data) for selected Puget Sound Lowland (PSL) streams that would demonstrate the validity and viability of such an indicator-based approach.

Specific tasks in the development and testing of indicators for streams:

1. Using a literature review, discussions with regional experts, and discussions with the Science Review Team (SRT), develop a set of metrics that are indicators of relationships between flow and biology in urban streams.
2. Identify and compile existing data that can be used to evaluate these metrics.
3. Use exploratory statistics to determine the utility of these metrics as hydrological and biological indicators in urban streams.

Hydrologic metrics were calculated from both stream gauge data and simulated (HSPF – Hydrologic Simulation Program Fortran) flow data. Metrics were calculated for a set of streams representing a range of urban and suburban land cover conditions to evaluate the effects of differences in hydrology on biological condition. Biological data sets were benthic macroinvertebrate community data collected for the regional benthic index of biotic integrity (B-IBI). The B-IBI integrates a number of biological attributes, using benthic macroinvertebrates, to assess the biological condition of a specific site (Karr 1981, Karr and Chu 1999). Metrics tested included the ten standard B-IBI metrics, the aggregate index based on scores of the ten metrics (B-IBI), and additional taxa richness or life history metrics. Visual inspection of bi-variate plots as well as exploratory statistical analysis showed that most hydrologic metrics are correlated with percent effective impervious area (percent EIA), several biological metrics are correlated with hydrologic metrics, and hydrologic metrics discriminate among sites grouped by biological condition as represented by the B-IBI. The findings from this first phase of the NFP suggest the following.

HSPF or other simulation models have utility in evaluating hydrologic change and relating these changes to biological condition, as well as for simulating future development and/or restoration scenarios for managers. However, this study demonstrates that simulation models should be used with caution until they can be specifically calibrated for flow metrics of biological interest.

The comparison of metric values from stream gauge and HSPF sources suggests that some of the flow metrics that we chose because of their expected biological significance are not well estimated by HSPF models. Most of the metrics were significantly different when calculated from the two data sources. However, a small number of the metrics we tested were not different between HSPF and stream gauge data. These metrics can be used with HSPF models, using standard calibrations, to evaluate flow alteration in PSL streams:

- Low pulse count (pulse events with low-flow threshold)
- High pulse count (pulse events with high-flow threshold)
- High pulse range (period of the year with high pulses)
- Fall rate (average daily rate of fall for falling portions of the hydrograph)
- % of time above the mean 2-year flow (proportion of year with flows above the 2-year mean flow)
- Date of onset of fall flows (date of the first increase in flows following summer low-flows)
- T_{Qmean} (proportion of the year daily mean discharge exceeds annual mean discharge)

This study demonstrates that a small number of flow metrics may be used to capture biologically relevant aspects of flow alteration in PSL streams. With further work to verify the relationships, the combination of flow and biological indicators suggested here could be used explicitly to inform management applications, such as the evaluation of stream ecosystem condition and development of restoration plans or stream management programs.

Several of the individual biological metrics we tested have the potential to provide diagnostic information about flow conditions. The percent of Baetid individuals, Clinger taxa, and the number of taxa that are univoltine plus semivoltine are metrics that can provide diagnostic information about particular flow stresses that may be important and present in a given system. Benthic macroinvertebrate taxa that are expected to tolerate flow disturbances (resistant), or recover better from disturbances (resilient), may be sensitive indicators of the type and degree of flow alteration in PSL streams.

The flow metrics with the best correlations with biology include those that indicate a change in disturbance regime (intensity, duration, or frequency of disturbance) or a change in the timing of flow events. This set captures various aspects of the flow regime (magnitude, frequency, duration, timing), minimizes redundancy among flow metrics, and has strong correlations with biological metrics:

- Low-flow threshold pulse events and interval between pulses
- High-flow threshold pulse events and total period of the year with high pulses
- T_{Qmean}
- Percent of time above the mean 2-year flow
- Timing of the onset of fall flows

This study also suggests the potential for developing an index of hydrologic integrity (IHI) for urban PSL streams. Such an index would combine flow metrics that are correlated with biological metrics, are correlated with increasing urbanization measured as percent EIA, and together capture major attributes of the flow regime (i.e., magnitude, duration, frequency, timing, rates of change). An index of hydrologic integrity could be used to assess the relative condition of stream systems in terms of flow, and suggest which components of the flow regime should be the focus of restoration efforts. Constructing an IHI from biologically relevant flow metrics, as identified here for PSL streams, could provide managers with an easy to use and meaningful tool for assessing stream condition, in combination with other commonly used tools such as the B-IBI, RIVPACS, or habitat indices.

1.0 INTRODUCTION

The flow regime of rivers and streams strongly influences aquatic communities, and alterations to natural flow regimes result in a number of impacts, including reduced biodiversity and loss of native populations (Poff et al. 1997, Paul and Meyer 2001, Bunn and Arthington 2002). Flow regimes in many Puget Sound Lowland (PSL) streams have been significantly altered over the past 150 years by a number of human actions, including logging, conversion of forest to residential, commercial, and industrial uses, draining and filling of wetlands, surface and groundwater withdrawals, channel straightening, diking, dredging, and filling, and regulation of river flows for flood storage and hydroelectric power generation (Spence et al. 1996, Konrad 2000, Booth et al. 2004). Protecting or restoring natural flow regimes is important for sustaining and recovering healthy aquatic ecosystems (Poff et al. 1997). Because restoring completely natural flow regimes is not always possible in altered systems, the term 'normative flow' was developed to refer to a flow regime that resembles the natural flow regime sufficiently to sustain all life stages of a diverse suite of native species. The use of normative flow concepts and approaches (see Fuerstenberg et al. 2002, Conceptual Framework) shows great promise in addressing the complex and difficult issues surrounding anthropogenic flow alteration.

The Normative Flow Project (NFP) began in 2001 with the goal of developing an ecologically-based flow assessment method that could be used by King County resource managers to (a) evaluate the effects of past, present, and future water and land management actions on the flow regimes of streams and rivers; (b) evaluate the effects of altered flow regimes on the physical and biological conditions in rivers and streams; and (c) guide management actions to reduce these effects through mitigation, protection, and restoration of flow regimes that support ecosystem integrity and salmon conservation.

The project uses an indicator-based approach for its analytical and assessment method. A first step is to link measures of hydrologic change in PSL streams as directly as possible with observed biological conditions in streams where both hydrologic and biological data are available. Results will be used to develop tools and guidance for managers using hydrologic and biological measures as indicators for evaluating and mitigating the impacts of hydrologic alteration on streams. This report summarizes work to date on an indicator-based approach for urban streams. It introduces the indicator approach and methods, reports results of the initial tests linking flow metrics and biological metrics, and discusses the results and recommendations for the use of indicators in developing a flow assessment method.

Additional information on the NFP, including copies of the conceptual framework document, literature review summary, and preliminary indicators list, can be found on the project web site:

http://dnr.metrokc.gov/wlr/BASINS/flows/

1.1 Objectives of the Normative Flow Project

To accomplish the project goals, the following objectives established the framework for the streams indicator analysis:

- Develop a valid and defensible set of hydrologic and biological indicators as a basis for flow assessment.
- Develop new analytical tools (e.g., models, databases) and/or adapt existing tools to support the assessment method.
- Formulate flow management recommendations based on the assessment and analytical methods.
- Use the flow management recommendations to inform technical, regulatory (e.g., permitting), and policy decisions specific to King County.
- Monitor and evaluate the effectiveness of management actions based on Normative Flow concepts.

Steps towards meeting the project objectives are outlined in Figure 1. This report documents work completed toward meeting the first two objectives listed above, and describes the outcomes of Steps 3 and 4 (Figure 1).

The focus of this work is on smaller (e.g., less than 4^{th} order, Strahler 1:24,000) streams in urban or urbanizing watersheds. Because larger riverine ecosystems differ substantially from smaller streams in hydrology, rates and magnitudes of geomorphic processes, and in certain aspects of biology, this project has fostered the discrete development of tools and guidance for streams (1^{st} to 4^{th} order) and rivers (greater than 4^{th} order). This project also recognizes that hydrologic alteration may be driven by different actions at the stream scale compared to the river scale. Hydrologic alteration in streams in the PSL is primarily driven by the suite of changes that occur with urbanization, while hydrologic alteration in larger rivers is strongly influenced by river regulation for flood control, channel modifications such as dredging and straightening, water storage in large reservoirs for municipal and agricultural uses, and hydroelectric power generation (Montgomery et al. 2003). Urbanization affects flow regimes through changes in land cover and impervious surface area, thereby altering runoff processes (Hollis 1975, Booth and Jackson 1997). Urban development can also significantly alter flow regimes via changes in channel networks, increased surface and groundwater diversions for municipal water supply, and significant interbasin transfers of flows, for example through diversions for water supply or wastewater treatment.

To provide practical tools for managers, the focus of this project is on the types of flow alteration that regional and local governmental agencies are most likely to influence. These include stormwater management policies and best management practices, land use zoning and development regulation, riparian buffer widths, forest cover retention, impervious surface limits, water re-use or flow augmentation with reclaimed water, low impact development practices, and habitat protection and restoration projects.

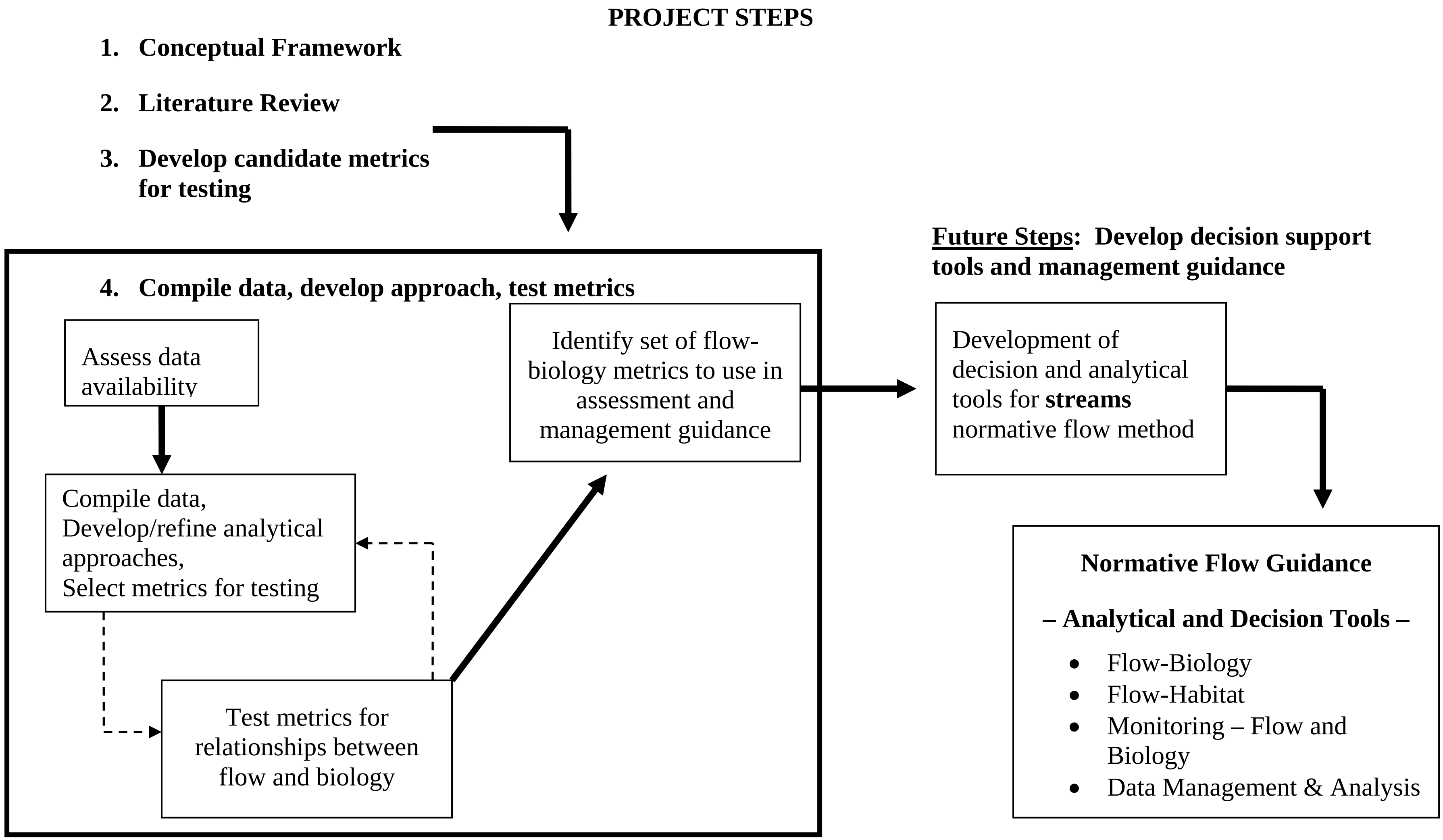


Figure 1. Steps Towards Meeting Project Objectives of Developing Assessment Tools and Management Guidance.

1.2 Streams Indicator Approach

1.2.1 Rationale for the Indicator Approach

A growing number of comparative studies relate flow alteration to physical or biological conditions in aquatic ecosystems (Poff et al. 1997, Paul and Meyer 2001, Bunn and Arthington 2002, Morley and Karr 2002). However, there is a lack of quantitative information about how specific flow changes are related to specific biological responses, especially in urban systems (Paul and Meyer 2001, Benda et al. 2002, Walsh et al. 2005, but see Booth et al. 2004, Roy et al. 2005, and Booth 2005).

This is due in part to the difficulties of integrating numerous physical and biological processes, which occur at a variety of spatial and temporal scales, into quantitative, predictive models. Quantitative tools for evaluating small-scale processes exist, but development of tools for larger spatial or temporal scales is limited, at least in part, by a lack of data (Benda et al. 2002). Long-term (i.e., >10 years) biological and hydrologic data records are generally not available for PSL streams, especially smaller urban streams, which limits the extent to which empirical data can be used to test hypotheses about relationships between flow alteration and biological responses. The data sets that do exist were not designed specifically to test these types of hypotheses. In addition, most of the work to date in defining measures of hydrologic alteration and identifying relationships between flow changes and biology has been conducted on large regulated rivers (Poff 1996, Poff et al. 1997, Bunn and Arthington 2002). Useful measures of hydrologic alteration and relationships between flow changes and biological response are likely to be different in small urbanizing streams (Booth et al. 2004).

We therefore focused on identifying a set of hydrologic and biological measures that can be used to evaluate changes in biological conditions in response to changes in flow conditions in PSL streams. The biological data set that is most extensive for PSL streams is the benthic macroinvertebrate data collected for the benthic index of biotic integrity (B-IBI) evaluations (Kleindl 1995, Karr and Chu 1999, Morley and Karr 2002). These data were collected as part of the regional effort to develop and use measures that describe the overall integrity or health of individual stream sites, using a multi-metric index (Karr and Chu 1999). Benthic macroinvertebrate data consist of counts of individual taxa (abundances), as well as ten individual B-IBI metrics and the aggregate B-IBI (Karr and Chu 1999).

We recognize that numerous other physical factors in addition to flow affect biological conditions in aquatic ecosystems (Figure 2). Data on most of these factors are even more limited than hydrologic and biological data in PSL streams. Habitat data would be extremely useful for evaluating the effects of flow changes on biology, because of the interactions between flow and habitat. Based on discussions with the Science Review Team (SRT), we considered several habitat measures that would be informative, including bed stability, bank stability, channel width and depth relative to flow, and canopy closure. However, these data were generally not available for sites with biological and flow data. Previous studies suggest that local riparian condition strongly influences biological condition in PSL streams (Morley and Karr 2002). Riparian canopy condition measures can be readily developed from existing GIS data for most of the PSL region. We therefore included measures of local riparian forest condition at the biological sampling sites to evaluate the relative influences of flow and local habitat condition.

By focusing primarily on relationships between flow and biology, we may be able to provide managers with practical tools for assessing and managing flows for sustaining desired biological conditions in urban streams. Our focus therefore, is to ask if there are consistent differences in flow conditions and biological conditions between streams expected to have highly altered flows (i.e., more urbanized) and streams expected to have less altered flows (i.e., relatively un-urbanized).

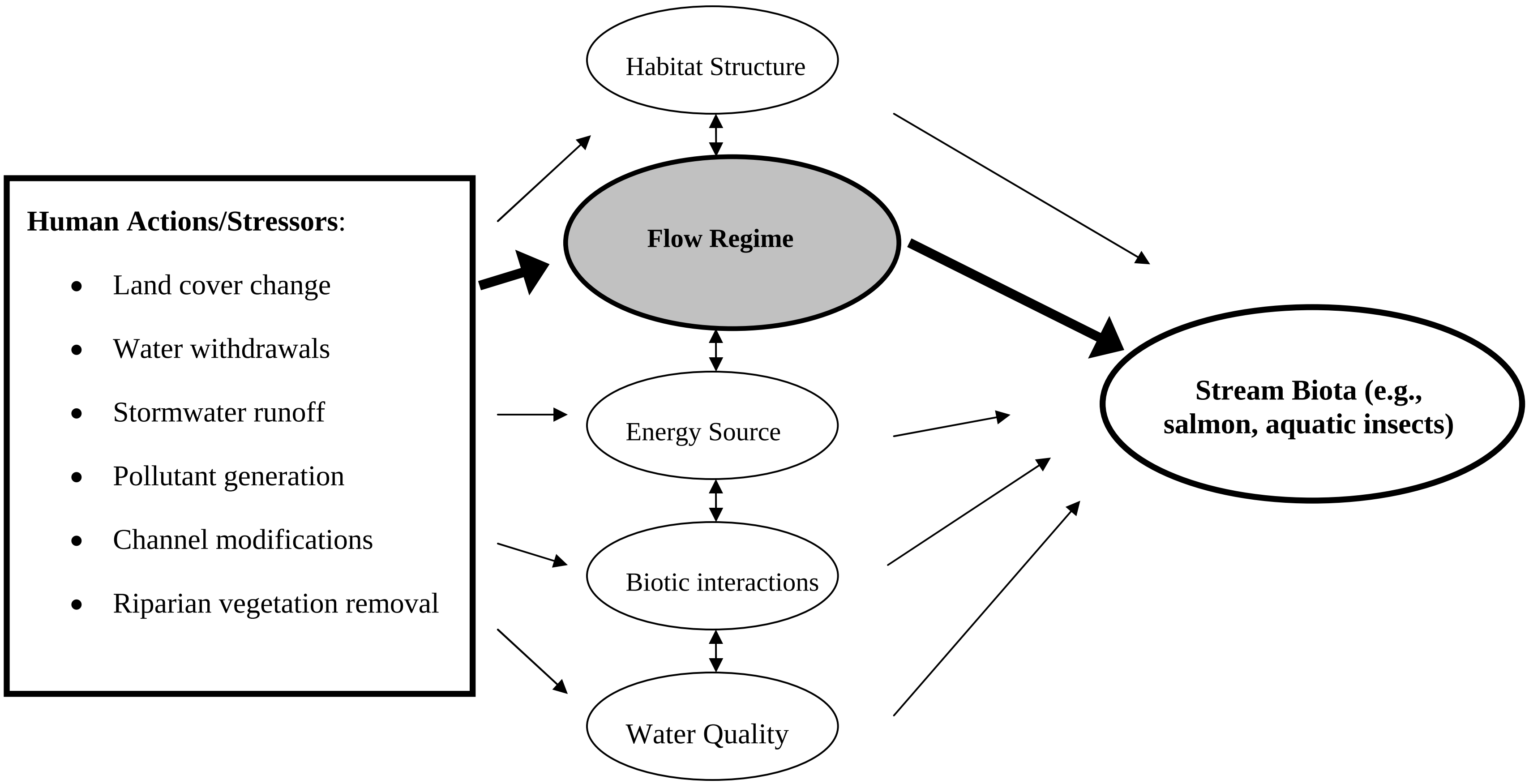


Figure 2. Interacting Factors (direct and indirect effects) Affecting Stream Biota – Project Focus is on Detecting Relationships Between Urbanization, Flow, and Biology (figure adapted from Karr and Yoder 2004 and discussions with the SRT).

1.2.2 Description of the Streams Indicator Approach and Analysis

Our approach was to identify measurable attributes of hydrology and biology that can be used to evaluate the ecological condition of PSL streams. Metrics are measurable attributes of geomorphology, hydrology, physical habitat or biology. Metrics that represent important aspects of stream ecosystems and show consistent responses to other environmental factors or human actions can be used as indicators. Specific tasks in the development and testing of hydrologic and biological metrics for streams are listed below; steps 1-2 include developing the conceptual framework for the project and conducting a literature review of biological responses to flow alteration (see Figure 1). Steps 3 and 4 represent the initial identification, screening, and preliminary tests of metrics presented in this report. Steps 5 through 8 describe additional steps required to complete development of management tools and guidance (see Figure 1).

3. Using a literature review, discussions with regional experts, and discussions with the Science Review Team (SRT), develop a set of metrics that are expected to be useful indicators of how urban stream biological conditions respond to changes in flow regimes.

4. Identify and compile existing data, and develop an analytical approach that can be used to evaluate these metrics. For PSL streams, benthic macroinvertebrate data are the most complete, readily available biological data set; data for other taxa (e.g., fish) are limited. Use exploratory statistics to determine the utility of these metrics as hydrological and biological indicators in urban streams.

If significant relationships are found between flow and biological metrics, then steps to complete the development of management tools include:

5. Verify/validate these metrics and identify this set of metrics for use within the Normative Flow framework to provide guidance for assessing and managing streams.

6. Develop protocols for building additional data sets appropriate for testing additional metrics against hydrologic change (e.g., fish, riparian biota, physical habitat).

7. Test and Verify/validate these additional metrics using new data sets.

8. Develop tools and guidance for managers using these metrics as indicators for evaluating and mitigating the impacts of hydrologic alteration on streams.

2.0 METHODS

2.1 Selection of Study Stream Basins

2.1.1 Identifying Stream Basins with Similar Hydrologic Regimes and Biological Conditions

To evaluate the effects of flow alteration on stream biota in urbanizing systems, it is important to select a group of streams that reflect a gradient of urbanization (and flow alteration), but which are otherwise similar in terms of precipitation regime, elevation, geology, and geomorphology. Selecting stream basins with similar climatic regimes, geology, physiography, and size should reduce the natural hydrological and biological variability due to these factors (Poff et al. 1996, Montgomery and Buffington 1998, Booth et al. 2003, Buffington et al. 2003), and increase the chances of detecting anthropogenic influences on hydrology and biology.

We initially identified a group of streams that are all low-elevation (less than 200 m above sea level), 1st to 5th order (Strahler 1957, 1:24,000), low gradient (2%-4% slopes), and located in the Puget Sound Basin between the Cascade Range and Puget Sound. The stream basins used in this analysis include eight basins within the Cedar-Sammamish watershed, as well as two streams that drain directly to Puget Sound or Lake Washington (Table 1). The area has a maritime climate with mild, rainy winters and dry summers. In our set of low-elevation streams, precipitation falls primarily as rain with most of the annual precipitation occurring between November and April. We expected that this group of streams would be similar enough in geology, physiography, and climatic regime to be characterized by similar natural flow regimes and responses to urbanization (Booth et al. 2003, Booth 2005).

Initial analyses of the set of 1st to 5th order streams indicated that when vegetation cover in the basin is similar, the smallest, higher gradient tributary streams (i.e., 1st order) differed in hydrology when compared to the larger 2nd to 4th order streams (SRT 2004). For example, the smaller tributaries in the Issaquah basin are slightly higher elevation, have higher gradients, and greater proportions of the basins are underlain by till soils or bedrock than the other streams in our data set. These smaller tributaries tend to be naturally flashier than streams with lower gradients and higher percentages of outwash soils in the basin. Therefore, including these streams may increase the likelihood that natural hydrologic variability in this set of streams will obscure changes in hydrology related to urbanization and decrease our ability to detect relationships between hydrologic changes due to urbanization and biological condition.

Benthic macroinvertebrate communities differ among streams depending on basin size, stream order, presence and type of riparian canopy, disturbance regime and history, basin land use, and channel geomorphology (Hershey and Lamberti 1998). Our biological data set was collected using protocols developed for sampling 2nd to 4th order PSL streams, and may not be applicable to larger or smaller systems (Fore et al. 1994, Kleindl 1995, Black and MacCoy 1999, Morley 2000, Morley and Karr 2002, Celedonia 2004). We assumed the group of streams selected to reduce natural hydrologic variability because they are similar in climate, geology, physiography, and predominant vegetation prior to urbanization, would also have been similar biologically prior to development. Therefore we used 2nd to 4th order streams to compare hydrological and biological conditions within the basins listed in Table 1.

Table 1. Stream Basins Included in the Analysis, Ranked in Order of Increasing Urbanization (as Percent Effective Impervious Area).

Stream Basin	Range of %EIA[1] in Sub-basins Defined for HSPF[2] Models	Average %EIA	Basin Size (acres)
Upper Taylor[3]	NA	<1%	11,000
Upper Rock[3]	NA	<1%	9,000
Issaquah	<1 – 3%	2%	38,523
Evans	3 - 7%	4%	2,000
Big Bear	2 - 8%	6%	31,895
Little Bear	6 – 12%	10%	10,000
Swamp	17 – 19%	18%	15, 676
Miller[4]	17 – 19%	18.5%	4,324
Madsen	20%	20%	1,419
Thornton[5]	24 – 30%	27%	2,100

[1] Percent of basin as effective impervious area (impervious area that drains directly to surface waters); estimated values from HSPF models, average value for all sub-basins within each basin.

[2] HSPF – Hydrologic Simulation Program Fortran

[3] Stream gauge data only

[4] Drains directly to Puget Sound.

[5] Drains directly to Lake Washington.

2.1.2 Gradient of Urbanization

Ideally, to develop indicators of flow alteration in PSL streams, relationships between flow and biology would be evaluated for a set of streams in which environmental factors are similar, except for the degree and type of flow alteration. In regulated rivers, before and after comparisons (e.g., pre- vs. post-dam construction) can be made where flow regulation is the only or primary factor that has changed. If flow alteration has occurred over time, for example, due to urbanization, then trends in hydrological and biological condition over time can be compared. All of the streams in the PSL are subject to multiple human alterations and differ in numerous environmental factors other than flow (Booth et al. 2004), so there are no streams that differ only in flow alteration. There are no long-term (i.e., more than 50-100+ years) streamflow records or biological data from PSL streams, which pre-date large-scale logging or land conversion. It is therefore not possible to do before/after comparisons of unaltered flow regimes and altered flow regimes in the same system using empirical methods alone. The PSL also lacks long-term biological records, especially in streams, so that comparisons of trends in biological condition with hydrologic change over time are not possible.

Therefore, we used a 'space for time' substitution approach by selecting a set of stream basins that reflect a range of land cover conditions, from relatively rural and forested basins (e.g., Issaquah and Big Bear) to highly urbanized, basins, based on percent effective impervious area[6] (EIA) (e.g., Miller and Thornton) (Table 1). Our gradient of urbanization is represented by percent EIA. The greatest differences in percent EIA, or the largest gradient of urbanization occurs between basins; there are gradients within basins as well, as reflected in the range of percent EIA within Big Bear and Little Bear basins (Table 1). Because urbanization encompasses a number of actions that alter runoff processes and stream flows, we expected the percent EIA gradient to reflect a similar gradient in the extent of hydrologic alteration (Hollis 1975, Konrad and Booth 2002).

In the Puget Sound region, there are currently few examples of lower gradient, low-elevation streams with forested or non-urbanized basins. Most of the forested basins remaining in the PSL are smaller, higher gradient, higher elevation systems, which are likely to be significantly different from low gradient, low-elevation, larger systems in natural flow regimes (Buffington et al. 2003). Most of the lower elevation, low gradient systems are in urban and suburban areas. Hydrologic data do not exist to approximate historical or pre-disturbance conditions for PSL streams because low gradient, 2nd and 4th order stream basins began urbanizing before long-term stream flow data were collected. The addition of a few sites on the forested, but low gradient end of the range (City of Seattle Cedar Water Supply Watershed – Upper Taylor and Upper Rock) allowed us to expand the range of current land cover conditions in our data set (Table 1).

[6] Effective impervious surfaces are those impervious surfaces (surfaces that do not infiltrate runoff - roofs, parking lots, sidewalks, etc.) that drain directly to a surface water conveyance system and there is no opportunity for runoff to infiltrate prior to reaching surface water.

We selected stream basins that reflected gradients of urbanization both within basins and across basins to determine if relationships between hydrologic metrics and benthic macroinvertebrate metrics are basin-specific or general to a group of stream basins. Inter-basin differences in percent EIA are greater than intra-basin variability; however, there is some intra-basin variation in percent EIA as well, particularly in the Big and Little Bear basins (Table 1). If there are large, inherent differences among the stream basins in natural flow regimes or macroinvertebrate communities, then these differences could be confounded with differences due to urbanization if differences in percent EIA are largely inter-basin differences.

2.1.3 Pairing Biology and Hydrology - Consistent Data Sets

To relate hydrologic alteration with biological condition, our analyses were limited to stream basins that have both biological and hydrologic data. The most highly urbanized streams are often so altered in terms of channel morphology, substrate conditions, and instream habitat, that there are few locations where biological data can be collected using the B-IBI protocols. Many of the benthic macroinvertebrate samples that were available for these highly urban streams did not have the minimum number of organisms required for B-IBI samples and could not be used in the analysis (see discussion below). The lack of biological data is undoubtedly related to anthropogenic impacts, including flow alteration, but the data limitations make it difficult to relate biological condition with hydrology in these streams.

2.2 Data Sets and Metric Calculations

2.2.1 Hydrological Data

2.2.1.1 Flow Data Used to Calculate Metrics

To calculate hydrologic metrics, we used Hydrologic Simulation Program – Fortran (HSPF) models to simulate flows and stream gauge records of observed flows. Hydrologic simulation models have been used in a number of studies to relate hydrologic changes to increasing levels of urbanization, or hydrologic changes with trends in urbanization over time (Booth and Reinelt 1993, MacRae 1996).

There are a number of advantages in using both HSPF and gauge data to calculate flow metrics. Use of simulation models allows a number of different land cover scenarios to be evaluated. For example, we can model fully forested conditions in each of our basins to represent the pre-development stream flows in cases where there are no gauge data that pre-date urbanization. Hydrologic (HSPF) models also allow ‘before/after’ comparisons to estimate the degree of departure or hydrologic alteration by comparing flows under current land cover conditions to flows under fully forested conditions. In addition, simulation models would allow a range of future development scenarios to be evaluated by managers interested in assessing the impacts of different development and/or mitigation scenarios on hydrologic and biological condition.

Although gauge data is more representative of actual stream conditions, it is also more limited, and gauges are frequently not in the same location as biological sampling sites. There are relatively few stream gauges with longer-term (> 10 years) periods of record on small streams in the PSL. Most streams have a single gauge at the mouth with some additional gauges at confluences between larger tributaries and the mainstem. Flow conditions at these gauges may not reflect the hydrologic conditions in upstream reaches, where many of the biological sampling sites are located. Simulation models can be run at multiple locations or sub-basins within each basin, allowing greater spatial representation of hydrologic conditions and better spatial pairing of flow data with biological sampling sites.

HSPF Simulation-Model Flow Data

Each of the stream basins in our set had previously been divided into sub-basins for the purposes of developing HSPF models. We selected hydrologic sub-basins within each basin for the purpose of spatially pairing the hydrologic and biological data. Flows were simulated for the downstream-most point of each sub-basin, defined as a 'point of interest' (POI) for that sub-basin.

Existing, calibrated HSPF models were run for each POI in each of our basins to derive hourly flows over a 52-year period of record (1950-2002), for two different land cover conditions. Models were run for historical or fully-forested land cover condition, and a current land cover condition. Current land cover was defined as land cover values from 1995, the latest year for which all the models had land cover data. All the HSPF models used the same translation of land use categories to land cover categories. The fully-forested land cover condition was used to estimate 'natural flow' conditions for each basin. The 1995 land cover condition was used to estimate flows under the current (i.e., 1995) levels of urbanization in each sub-basin.

Prior to this project, the HSPF models were calibrated using short-term local precipitation records for each basin, to represent actual precipitation which occurred during the calibration period. All the selected basins had at least a few years of continuous observed streamflow data that could be used to calibrate the HSPF models. Longer-term local precipitation records are not available for all the basins in our data set. Therefore, the long-term flow data were generated using the 52-year historical precipitation record developed from observations at Sea-Tac International Airport, the closest long-term precipitation records available for these stream basins. The same 52-year historical precipitation record was used to generate flow data under both the fully-forested and the current land cover conditions. This allowed us to compare a simulated *no-development condition* and a simulated *with-development condition* for each stream basin using the same precipitation record.

Development of the HSPF Models

In HSPF, *pervious land segments* (PERLNDS) are used to define different combinations of soil and land cover types. Soil types used in the models include till, outwash, bedrock, and saturated soils. The land cover types include forest, pasture grasslands, urban lawn, wetlands, and impervious. In some of the basin models, PERLNDS were further differentiated using slope and/or elevation of the pervious land segments.

Percent EIA is defined in the HSPF models based on estimates of pervious and impervious land segments within each basin or sub-basin of the model. Impervious surfaces are all surfaces that do not infiltrate runoff, such as roofs, parking lots, roads, sidewalks, and driveways. Effective impervious surfaces are those impervious surfaces that drain directly to a surface water conveyance system (i.e., there is no opportunity for runoff to infiltrate prior to reaching a pipe, ditch or stream). Estimates of pervious and impervious land segments are derived from a variety of GIS data including soil types (till, outwash, saturated soils, bedrock), land use coverages that are translated into vegetation/land cover categories, and road surface coverage. The determination of which impervious surfaces are effective impervious surfaces is estimated using average EIA values for each land use category. These average values have been developed from previous experience with PSL watersheds (Dinacola 1989 Alberti et al. 2003). Sources of error in estimating EIA include categorizing land uses from images, translating land uses to vegetation classes or land cover types, assigning impervious/pervious segments to land use or land cover categories, and estimating average effective impervious area values for land cover types.

For the current land cover condition we used 1995 land cover data to determine the acreages of each PERLND type in 1995. The HSPF models for each basin also used existing wetland area and existing channel hydraulics for simulating the current condition. For the historic or fully-forested condition, we assumed that land cover was 100% forested, except in areas where there are existing lakes and wetlands. Prior to urbanization, these basins would have been predominantly forested, with relatively small areas of shrub or emergent vegetation (Collins et al. 2003). Because we do not have any measures of the relative area of forest vs. shrub or emergent vegetation under historical conditions for our stream basins, we assumed the basins were completely forested rather than attempting to estimate the extent of other vegetation types.

In addition to soils, topography, and land cover, runoff and streamflow will also be affected by channel morphology and the extent of wetlands, especially wetlands connected to stream channels. We do not have information on stream hydraulics or extent of wetlands under historical, pre-development conditions for any of our watersheds. The fully-forested condition therefore uses current wetland area. Because the current wetland area does not include wetlands that may have been filled or drained, the fully-forested land cover likely underestimates the historical extent of wetlands in each basin. In addition, these channels would have been influenced by large woody debris and beaver dams which would have strongly influenced stream flows and hydraulics (Buffington et al. 2003, Collins et al. 2003). Because our historical (fully-forested) model simulations use existing stream hydraulics, the effects of large woody debris, beaver dams or connected wetlands are not included in the fully forested simulated flow conditions.

Stream Flow Data Derived from Gauge Records

Stream gauge records from each of our basins were used to generate one hour incremental time-series flow data for the available period of record for each gauge. None of our streams had gauges that were operating for the entire 52-year period (1950-2002) used to generate flow data from the HSPF models, so it was not possible to use the same period of record for model and gauge data. To compile flow data for calculating hydrologic metrics from the gauge data, we used the same period of record for all the gauged streams. Continuous observed stream flow data were available for the gauged stream basins in our sample for the thirteen-year period from 1989-2002. The period of record for gauge data thus included the same years as included in the model data (1989-2002); however, the period of record for the HSPF model data was longer.

2.2.2 Spatial Pairing of Hydrologic and Biological Data Sets

Within each stream basin, we identified hydrologic sub-basins that contained B-IBI sampling locations[7] (Table 2, Figure 3). We had at least one sub-basin for which we could pair HSPF flow and benthic macroinvertebrate data in each of the stream basins listed in Table 1. For the sub-set of stream basins that had gauge data and B-IBI sampling locations near the gauge site, we paired B-IBI data with stream flow data derived from the gauges (Table 3, Figure 3). This allowed us to use both simulated flow data and observed flow data to calculate metrics. The two flow data sources were also used in separate, parallel analyses to evaluate relationships between urbanization gradients and hydrologic metrics, and between hydrologic metrics and biological metrics.

[7] Tables 2 and 3 include only those B-IBI sampling sites and years where at least 500 total organisms were collected (see discussion of B-IBI sampling protocols. Analyses were run only on sites with at least 500 total organisms.

Table 2. Stream Basins (2nd to 4th order) with HSPF Modeled Flow Data and B-IBI Data.

Basin	Sub-Basin	POI Name (M=mainstem; T=tributary and Stream)	%EIA upstream of POI	Stream Order	Data Source[8] and Years with B-IBI Data	B-IBI Site Code
Bear/Evans	Big Bear	T - 7 - Cottage Lake	6.8	2	1995 (KC), 1996 (KC), 1997 (KC), 1999 (KC), 2000 (KC), 2002 (KC)	BBCTL5_98
Bear/Evans	Big Bear	T - 8 –Upper Cottage Lake	6.0	2	2002 (KC)	BBCTL8_31
Bear/Evans	Big Bear	T - 6 - Daniels	6.2	2	1997 (KC), 1999 (KC), 2000 (KC)	BBDAN0_79
Bear/Evans	Big Bear	T - 3 - Seidel	2.0	2	1997 (UWM), 2002 (KC)	BBSE01
Bear/Evans	Big Bear	M - 11 - Upper Big Bear	2.5	2	1995 (KC), 1997 (UWM), 1999 (KC), 2000 (KC), 2002 (KC)	BBBBR5_03
Bear/Evans	Big Bear	M - 12 - Middle Big Bear	4.1	3	1994 (UWKL), 1997 (UWM)	BBBBR2_82
Bear/Evans	Big Bear	M - 13 - Lower Big Bear	6.0	4	1994 (UWKL), 1995 (KC), 1997 (UWM), 1997 (KC), 1999 (KC), 2002 (KC)	BBBBR6_58
Bear/Evans	Mackey	T - 4 - Mackey	3.0	3	1998 (KC), 1999 (KC)	BBMA0_15
Bear/Evans	Evans	M - 21 - Lower Evans	7.0	3	1999 (KC), 2000 (KC), 2002 (KC)	BBEVN1
Bear/Evans	Evans	M - 15 - Middle Evans	5.0	3	1996 (KC), 1998 (KC), 1999 (KC), 2000 (KC), 2002 (KC)	BBEVN2
Bear/Evans	Evans	M - 14 - Upper Evans	3.0	2	1995 (KC)	BBEVN3
Issaquah	Carey	T - 1 - Carey	1.0	2	1995 (KC), 1996 (KC), 1998	ISCAR1

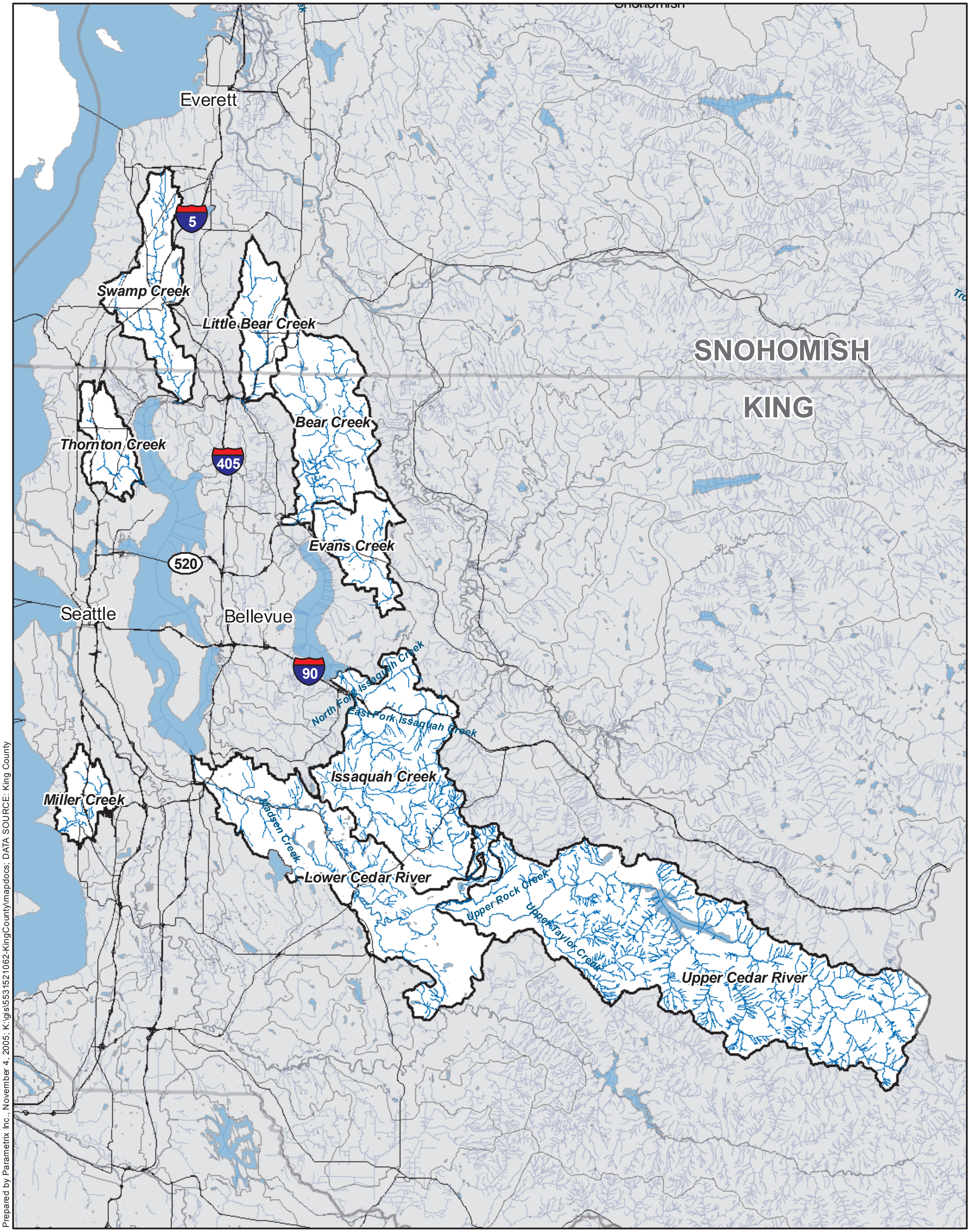
[8] Data Source: UWK = J. R. Karr; UWM = S. R. Morley; UWKL = Kleindl; KC = King County DNRP; SC = Snohomish County; SPU = Seattle Public Utilities

Basin	Sub-Basin	POI Name (M=mainstem; T=tributary and Stream)	%EIA upstream of POI	Stream Order	Data Source[8] and Years with B-IBI Data	B-IBI Site Code
					(KC), 2000 (KC), 2002 (KC)	
Issaquah	Carey	T - 1 - Carey	1.0	2	1994 (UWKL), 1995 (UWK)	ISCAR1_1
Issaquah	Holder	T - 2 - Holder	<1	2	1997 (KC), 1998 (KC), 2000 (KC), 2002 (KC)	ISHOL1
Issaquah	N. Fork Issaquah	T - 8 - N. Fork Issaquah	2.0	2	1996 (KC), 1998 (KC), 2000 (KC), 2001 (KC), 2002 (KC)	ISNF1
Issaquah	E. Fork Issaquah	T - 7 - Lower E. Fork Issaquah	<1	3	1996 (KC), 1998 (KC), 2000 (KC), 2002 (KC)	ISEF1
Issaquah	E. Fork. Issaquah	T - 5 - Upper E. Fork Issaquah	<1	2	2002 (KC)	ISEF3
Issaquah	Issaquah	M - 11 - Middle Issaquah	1.0	3	1995 (KC), 1998 (KC), 2000 (KC), 2002 (KC)	ISISS3
Issaquah	Issaquah	M - 10 - Upper Issaquah	1.0	2	1995 (KC), 1998 (KC), 2000 (KC), 2002 (KC)	ISISS4
Little Bear	Little Bear	M - 6 - Little Bear 6	9.0	3	1994 (UWKL)	LBR0_11
Little Bear	Little Bear	M - 6 - Little Bear 6	9.0	3	2000 (SC)	LBR0_31
Little Bear	Little Bear	M - 6 - Little Bear 6	9.0	3	1995 (UWK)	LBR0_43
Little Bear	Little Bear	M - 5 - Little Bear 5	8.0	3	1997 (UWM)	LBR2_63
Little Bear	Little Bear	M - 5 - Little Bear 5	8.0	3	1994 (UWKL)	LBR2_79
Little Bear	Little Bear	M - 41 - Little Bear	7.0	3	1997 (UWM)	LBR3_0
Little Bear	Little Bear	M - 41 - Little Bear	7.0	3	1995 (UWK)	LRB3_3
Little Bear	Little Bear	M - 4 - Little Bear 4	6.0	3	1997 (SC), 2000 (SC)	LBR3_41
Little Bear	Little Bear	M - 4 - Little Bear 4	6.0	3	1997 (UWM)	LBR3_43
Little Bear	Little Bear	M - 4 - Little Bear 4	6.0	3	1994 (UWKL)	LBR3_52
Little Bear	Little Bear	M - 3 - Little Bear 3	6.0	3	1995 (UWK)	LBR5_15

Basin	Sub-Basin	POI Name (M=mainstem; T=tributary and Stream)	%EIA upstream of POI	Stream Order	Data Source[8] and Years with B-IBI Data	B-IBI Site Code
Little Bear	Little Bear	M - 3 - Little Bear 3	6.0	3	1994 (UWKL)	LBR5_32
Little Bear	Little Bear	M - 32 - Little Bear	7.0	2	1995 (UWK)	LBR6_28
Little Bear	Little Bear	M - 31 - Little Bear	8.0	2	1997 (SC), 2000 (SC)	LBR6_85
Little Bear	Little Bear	M - 31 - Little Bear	8.0	2	1997 (UWM)	LBR6_91
Little Bear	Little Bear	M - 2 - Little Bear 2	12.0	2	2000 (SC)	LBR7_57
Madsen	E. Fork Madsen	T - 1 - E. Fork Madsen	20	3	2000 (KC), 2002 (KC)	CDEFM1
Swamp	Swamp	M - 1 - Upper Swamp	19	2	2002 (SC)	SWMP5
Swamp	Swamp	M - 2 - Upper-Middle Swamp	19	2	1995 (UWK)	SWMP4
Swamp	Swamp	M - 3 - Middle Swamp	17	3	1995 (UWK)	SWMP3
Swamp	Swamp	M - 3 - Middle Swamp	17	3	1994 (UWKL), 1995 (UWK), 1997 (UWM), 2002 (SC)	SWMP2
Swamp	Swamp	M - 5 - Lower Swamp	18	4	1997 (SC), 2002 (SC), 2002 (KC)	SWMP1
Thornton	Thornton	M - 2 - Thornton	30	2	1994 (UWKL), 1999 (SPU), 2000 (SPU), 2001 (SPU)	TH04 (TM01)
Thornton	Thornton	M-7-Thornton	24	2	1994 (UWKL), 1998 (SPU), 1999 (SPU), 2000 (SPU)	TH01 (TN01)
Thornton	Thornton	M-5-Thornton	25	3	1996 (SPU), 1998 (SPU), 1999 (SPU), 2000 (SPU), 2001 (SPU)	TH02 (TM02)

Table 3. Stream Basins (2nd To 4th Order) with Gauged Stream Flow Data and B-IBI Data.

Basin & Sub-Basin	POI Name (M=mainstem; T=tributary)	% EIA Upstream of POI	Stream Order	Data Source and Years with B-IBI Data	B-IBI Sampling Site Code
Bear Evans/Big Bear	M - 11 - Upper Big Bear	2.5	2	1995 (KC), 1997 (UWM), 1999 (KC), 2000 (KC), 2002 (KC)	BBBR5_03
Bear Evans/Big Bear	M - 13 - Lower Big Bear	6.0	4	1994 (UWKL), 1995 (KC), 1997 (UWM), 1997 (KC), 1999 (KC), 2002 (KC)	BBBR6_58
Bear Evans/Evans	M - 21 - Lower Evans	7.0	3	1999 (KC), 2000 (KC), 2002 (KC)	BBEVN1
Little Bear	M - 6 - Little Bear 6	9.0	3	2000 (SC)	LBR0_31
Little Bear	M - 6 - Little Bear 6	9.0	3	1995 (UWK)	LBR0_43
Little Bear	M - 6 - Little Bear 6	9.0	3	1994 (UWKL)	LBR0_11
Issaquah	M - 10 - Upper Issaquah	<1	2	1995 (KC), 1998 (KC), 2000 (KC), 2002 (KC)	ISISS4
Issaquah/E. Fork Issaquah	T - 7 - Lower E. Fork Issaquah	<1	3	1996 (KC), 1998 (KC), 2000 (KC), 2002 (KC)	ISEF1
Madsen/E. Fork Madsen	T - 2 - E. Fork Madsen	20	3	2000 (KC), 2001 (KC)	CDEFM1
Swamp	M - 5 - Lower Swamp	18	4	1997 (SC), 2002 (SC), 2002 (KC)	SWMP1
Thornton	M – 5 – Thornton	25	3	1996 (SPU), 1998 (SPU), 1999 (SPU), 2000 (SPU), 2001 (SPU)	TH02
Cedar/Rock - Seattle	M - 1 - Upper Rock Mouth	<1	3	1995 (SPU), 1996 (SPU), 1999 (SPU)	UROC1
Cedar/ Upper Taylor	M - 3 – Upper Taylor	<1	3	1995 (SPU), 1996 (SPU), 1999 (SPU)	TAY3



King County
Normative Flow Project

0 17,000 34,000 Feet

N

County Boundary
Waterbody
Drainage Basin
State Highway
River

Figure 3
Stream Basins and Sub-basins Included in the Analysis

2.2.3 Existing Biological Data Sets

The biological data set that is most extensive for PSL streams is the benthic macroinvertebrate data collected for developing the B-IBI or monitoring benthic macroinvertebrate communities (Kleindl 1995, Karr and Chu 1999, Morley and Karr 2002, Wiseman et al. 2003). Benthic macroinvertebrate data have been collected in PSL streams since 1994; however, at most sites data are not collected every year, so that continuous records are not available for any individual site. Most sites included in our analyses had 2-4 years of macroinvertebrate data (see Table 2 and Table 3); however, some sites had only a single year of data. Benthic macroinvertebrate metrics were calculated for each individual site and year; multiple sites within POI's or multiple years at a site were not combined.

2.2.3.1 Data Collection and Processing Protocols

Because B-IBI data were collected by multiple researchers, we screened these data sets to ensure that all data included in the analyses were collected using similar protocols (Kleindl 1995, Fore et al. 1996, Morley 2000). Invertebrates were collected in mid-August to mid-to-late September, using a Surber sampler to collect three samples along the mid-line of a representative riffle, or at three representative riffles within a reach at each sampling site. The three samples were either processed and taxa were identified and counted separately (Doberstein et al. 2000); or composited from the three samples (King County 2002).

One of two regional experts (Rhithron Biological Associates and Aquatic Biology Associates) identified the taxa or confirmed the identifications for all data sets used in this analysis. Taxa were identified to genus where possible, with some taxa being identified to Family or Order (Kleindl 1995, Morley 2000). Attributes (i.e., feeding group, voltinism) were assigned to all taxa using the same references as previous B-IBI studies in the PSL (Kleindl 1995, Merritt and Cummins 1996, Morley 2000).

Preliminary analyses showed that B-IBI and some individual metric values were consistently lower in the year 2000 than for years before or after 2000 at the same site. Review of the sample collection protocols indicated that some of the 2000 samples were collected later in the year than is standard for B-IBI sampling. The standard B-IBI sampling protocol prescribes sampling times that occur when the greatest number of taxa are present, flows are stable, and collection sites are physically accessible (Karr and Chu 1999). In PSL basins, this is roughly from early September to early October, prior to winter rains and high water (Morley and Karr 2002). Year 2000 samples that were collected in late October or early November were taken after the rainy season had started and may reflect significantly different physical and biological conditions than samples collected earlier in the season. Year-2000 samples were excluded from the analysis if they were not collected before mid-October.

2.2.3.2 Data Sources

Data sources included University of Washington researchers, King and Snohomish County natural resource agency staff, and Seattle Public Utilities staff. Benthic macroinvertebrate data collected by different groups, including volunteer groups, are comparable when consistent protocols are used (Fore et al. 2002). We screened data sets for inclusion based on the use of consistent protocols as described for each data set. However, because we could not verify that those protocols were actually followed for a particular data source, we examined the data set for consistent differences due to data source. We visually inspected scatterplots of benthic macroinvertebrate metric values from all data sources against percent EIA to determine if individual sources consistently resulted in outliers.

2.2.3.3 Minimum Sample Size

Individual benthic invertebrate samples were included in the analysis only if the total count for the sample was greater than 500 (Fore et al. 1996, Karr 1998, SRT 2004). Preliminary analyses did not reveal a clear effect of total number of individuals in the sample on B-IBI metrics or on bivariate relationships between hydrologic and biological metrics. However, when bivariate hydrologic and biological metric plots were examined, there was less scatter when only samples with more than 500 total organisms were included. Because many of the B-IBI metrics and the biological metrics tested here are richness measures, they are sensitive to the total number of organisms collected and sampling effort (Fore et al. 1996, Karl et al. 2000). Several of the samples from highly urbanized streams (e.g., Swamp, Madsen, Miller, and Thornton) had fewer than 500 total organisms and these samples were not included in the analyses.

2.2.3.4 Use of B-IBI Data for Testing Flow-Biology Relationships

The B-IBI data collection protocols for sampling in the PSL region were not designed to test specifically for the effects of flow on B-IBI metrics (Kleindl 1995, Karr and Chu 1999). In developing the B-IBI for PSL streams, sites and stream basins were selected to represent a range of land cover conditions that reflect an urbanization gradient that integrates multiple stressors on stream organisms (Kleindl 1995, Morley 2000). In applying the B-IBI to characterizing stream health, sites are typically selected to evaluate the biological condition at a given site, or to monitor the effects of stream restoration projects, development (e.g., new roads or housing developments), or sources of organic or inorganic pollution (Karr and Chu 1999, Morley and Karr 2002). In addition, B-IBI samples are collected in riffles, so that pool or other non-riffle habitats are not sampled and changes in these habitats may not be captured using B-IBI data.

Macroinvertebrate sample locations were paired as closely as possible with hydrologic POI's so that we could match macroinvertebrate metric values at that site with hydrologic metric values for that POI or sub-basin. Macroinvertebrate metric values were computed for each B-IBI sampling site and year. Because the B-IBI integrates both local, site-specific influences and basin-wide influences on stream biota, we defined some POI's to include more then one B-IBI sampling site. Hydrologic POI's with multiple B-IBI sites would allow us to compare the relative influence of sub-basin scale hydrology and local scale land cover on benthic macroinvertebrate metric values.

2.3 Defining and Selecting Metrics for Testing

2.3.1 Defining and Selecting Hydrologic Metrics

2.3.1.1 Defining Hydrologic Metrics

Hydrologic metrics were defined using a combination of literature review, discussions with the SRT, and inspection of differences in pattern between fully-forested land cover and 1995 land cover HSPF hydrographs. The flow category (magnitude, duration, frequency, timing, rate of change) and individual metrics screened for testing against benthic macroinvertebrate metrics are listed and defined in Table 4. The rationale for selecting these metrics for screening is summarized in Table 5.

Inspecting Hydrograph Patterns to Define Metrics

Using simulated flow data, hydrographs for fully-forested and 1995 land cover conditions were used to compare patterns in flow regimes for each POI under fully-forested and 1995 land cover conditions. We used the hydrographs and discussions with the SRT to guide our initial evaluation of hydrologic metrics that best captured the types of flow changes occurring in urbanizing PSL streams. We focused on metrics for which we could develop a plausible link between aspects of flow and direct or indirect effects on stream organisms (Table 5). For example, one dramatic difference between hydrographs in more urban vs. more forested basins is the occurrence, in the urban basins, of frequent small to moderate flood peaks following precipitation events in mid- to late-summer and early fall. A more fully forested basin in the PSL is typically able to absorb these precipitation events without generating significant surface runoff or storm pulses during the dry season (Booth and Jackson 1997). In forested basins, summer and early fall are periods with low but stable baseflow. The frequent atypical summer and early fall runoff peaks that occur in urban PSL streams constitute a change in timing and an increase in the extent and type of disturbance in the system. To capture these and other hydrologic alterations, we developed several new hydrologic metrics (Table 4):

- the change in frequency of flow pulses during different times of the year (i.e., high-flow pulses and low-flow pulses),
- the period of undisturbed, stable flows between pulses (high and low-flow pulse durations),
- the number of days in a year within the period disturbed by pulses for high-flow and low-flow periods (high or low pulse ranges), and
- the difference in timing of the first autumn flow that exceeds summer baseflow (onset of fall flows).

Table 4. Metric Definitions for Hydrologic Metrics Screened for Testing Against Biological Metrics.

METRIC NAME	METRIC DEFINITION/REFERENCE
	Magnitude of Low and High Flows
1-Day Annual Minima	Minimum 1-day annual daily flow-rate (cfs) for each calendar-year.
7-Day Annual Minima	7-day average minimum flow-rate (cfs) for each calendar-year. (e.g., 1990 is 01/01/90-12/31/90).
1-Day Annual Maxima	Maximum **daily** flow-rate (cfs) for each water-year (e.g., 1990 is 10/1/89-9/30/90)
Hourly Annual Maxima	Maximum **hourly**[9] flow-rate (cfs) for each water-year.
	Frequency of High and Low Flows (LARGE EVENTS)
Low Pulse Count	Number of times that the daily-time-step hydrograph pulses above the low-flow threshold for each calendar-year. Low flow threshold is set at 50% of the average flow-rate under forested conditions over full period of record.
High Pulse Count	Number of times that the daily-time-step hydrograph rose above the high-flow threshold (200% of the average flow-rate under forested conditions over full period of record), for each water-year.
	Frequency of Small Pulse Events (SMALL EVENTS)
Fall Count (0.1 Rule)	The number of days in which the change in daily flow from the previous day was more than 10% of the current day's flow-rate and declining, for each water-year.
Rise Count (0.1 Rule)	The number of days in which the change in daily flow from the previous day was more than 10% of the

[9] We investigated metrics calculated with different time-steps to evaluate the effect of time-step on correlations of hydrologic metrics with percent EIA and correlations of hydrologic with biological metrics. Preliminary evaluations did not show any significant effects of time-step on these correlations; however, further exploration of the biological importance of different time-steps (e.g., very short term peaks or changes in rates vs. longer-term averages) would be useful in developing assessment tools.

METRIC NAME	METRIC DEFINITION/REFERENCE
	current days flow-rate and rising, for each calendar-year.
Flow Reversals	The number of times that a trend-change occurred (rising-limb to falling-limb and falling to rising both counted) in the daily-time-step hydrograph. Minor variations in daily flow (<2%) were not considered an occurrence.
	Duration of High and Low Flows (LARGE EVENTS)
Low Pulse Duration	Number of days between low pulse events, or the average number of days per occurrence that the hydrograph was below the low-flow threshold, for each calendar-year.
Low Pulse Range	The difference, in number of days, between the last and first times that the daily-time-step hydrograph crossed the low-flow threshold, for each calendar-year.
High Pulse Duration	Average number of days per occurrence that the hydrograph was above the high-flow threshold (200% of the average flow-rate under forested conditions over full period of record) for each water-year.
High Pulse Range	The difference in number of days between the last and first times that the daily-time-step hydrograph crossed the high-flow threshold (200% of the average flow-rate under forested conditions over full period of record), for each water-year.
	Timing of Flow Events
Date of the 1-Day Minimum	The Julian date of each annual daily minimum flow.
Onset of Fall Flows	The Julian date of the day after the annual 7-day minimum flow period for the year.
	Rates of Change
Fall Rate	The average rate of fall for all falling portions of the daily-time-step hydrograph, for each calendar-year.
Rise Rate	The average rate of rise for all rising portions of the daily-time-step hydrograph, for each calendar-year.
	‘Flashiness’

METRIC NAME	METRIC DEFINITION/REFERENCE
$T\text{-}_{Qmean}$ Annual	The percentage of time (or days per year) in a given water-year that the daily-time-step hydrograph was above the year's average forested flow-rate (based on Booth and Konrad 2002)
R-B Index	The average daily rate-of-change (absolute value) of the daily-time-step hydrograph, for each water-year. Baker et al. 2004.
% time above 2-year mean flow	The percentage of time (or days per year) that the **daily-time-step** hydrograph was above 2-year mean forested flow-rate, calculated individually for each water-year.
% time above 2-year mean flow	The percentage of time (or days per year) that the **15-minute time-step** hydrograph was above the 2-year mean forested flow-rate, calculated as a composite across all water-years of period of record.
	Stream Power, Geomorphically Active Flows, Storm-flow Events
Normalized Effective Stream Power	A measure of the effectiveness of the work of flow rates on the channel, based on half the 2-year or greater flow thresholds. Assuming that half the 2-year flow is a surrogate for the threshold for movement of channel sediments. Calculated by dividing the range of flows above 50% of the 2-year forested flow-rate (assumed threshold of movement of stream bed-sediments) into discrete flow ranges, take the average flow-rate of the range raised by a power of 2, multiplied by the amount of time the hydrograph spent within that flow-rate. Summing all discrete components yields a measure of stream power. Method requires normalization using fully-forested conditions. Calculate value individually for fully-forested and 1995-current conditions, and then divide fully-forested values into current values to yield the percentage increase in stream power between baseline and current.
Q2-Current :Q10-Fully-forested	Ratio of Current 2-year **hourly flow-rate** (cfs) to the Forested 10-year hourly flow-rate (cfs).
Runoff Event Count	Generated using hydrograph separation (nhc, 2004) that can be used to isolate baseflows and intermittent storm hydrographs for statistical evaluation. Number of discrete storm hydrographs generated by hydrograph separation routine, by water-year.
Runoff Event Duration - Mean	The average number of days for individual storm hydrographs, generated by water-year.
Runoff Event Duration - Max	The maximum number of days for individual storm hydrographs, generated by water-year.
	Relative Magnitude of Short-term Events (MAX/MEAN RATIOS)
DAY-Q MAX/MEAN	Ratio of annual maximum daily flow-rate (cfs) to the annual average daily flow-rate (cfs), by water-year.
Annual Max-Hour/Mean-Daily	Ratio of annual maximum hourly flow-rate (cfs) to the annual average daily flow-rate (cfs), by water-year.

Table 5. Rationale Linking Hydrologic Metrics to Biological Responses or Conditions.

Metric Number	Metric Name & Description	Notes and Rationale for Selecting the Metric
		Magnitude of Low and High Flows
14	1-Day Annual Minima	Lowest 1-day flow related to habitat availability and temperature during dry periods of year.
16	7-Day Annual Minima	Does not show strong response to % EIA; related to habitat availability and water temperature.
20	1-Day Annual Maxima	Correlated with hourly annual maximum; however both were evaluated to investigate effects of time-step on metric estimation.
57	Hourly Annual MAX	Compared to the daily maximum flow, the hourly maximum flow better captures instantaneous peak flows. In more forested basins, the difference between daily peaks and hourly peaks should be smaller than in urbanized basins. In urbanized basins, hourly peaks may be larger than daily peaks reflecting the more rapid response of stream flows to increased runoff rates.
		Frequency of High and Low Flows (LARGE EVENTS)
33	Low Pulse Count	A measure of drier season pulse events or disturbance frequencies. During periods of the year when baseflows are below the threshold (50% of the forested historical average) this measure is the number of times that storm runoff events push the hydrograph above the threshold. In PSL streams with forested basins, during summer low flow periods, runoff from precipitation is virtually non-existent and flows are low but stable throughout this period of the year. In more urbanized basins, runoff events that result in pulses above the threshold occur more frequently due to decreased infiltration and greater runoff rates.
40	High Pulse Count	A measure of the pulse events or disturbance frequency during higher flow periods of the year (above a high flow threshold of >200% MAF). In PSL streams with forested basins, during winter high flow periods, significant runoff from precipitation is rare; large runoff events are typically tied to relatively infrequent rain-on-snow events. Flows gradually increase during the rainy season and remain high but relatively stable throughout this period of the year. During rain-on-snow events, or extremely large storms, spikes in flow occur but with typically gradual rising and falling limbs. In more urbanized basins, runoff events that result in pulses above the threshold occur frequently due to decreased infiltration and greater runoff rates, especially during periods of heavy rain during winter months.

Metric Number	Metric Name & Description	Notes and Rationale for Selecting the Metric
		Frequency of High and Low Pulses (SMALL EVENTS)
52	Fall Count (0.1 Rule)	A measure of the number of times flows fall with a relatively small threshold (counts small fall in flow compared to the high and low pulse count metrics).
53	Rise Count (0.1 Rule)	A measure of the number of rises in the hydrograph with a lower threshold than the high and low pulse counts.
91	Flow Reversals	Frequent flow reversals would constitute a disturbance for organisms sensitive to changes in water depths, velocities or amount of habitat available. Frequent flow reversals could require greater energy expenditure, interfere with feeding behavior or efficiency, and reduce the availability of refugia.
		Duration of High and Low Flows (LARGE EVENTS)
34	Low Pulse Duration	This is a measure of the **time between low pulse disturbances** during periods of low flow, or the duration of the pulse-free period during drier times of the year. In forested basins, because low pulse events are rare, there are long periods of time between events. In more urbanized basins, because low pulses occur frequently, the time between low pulse events is shorter. If low pulses constitute a significant disturbance for stream organisms, then a shorter duration between pulse events results in less recovery time between disturbance events.
39	Low Pulse Range	A measure of the length of the time period, in total number of days, during which low pulse events are occurring. In more urbanized basins, there is a longer period of time between the first and last low pulse events than in more forested basins.
41	High Pulse Duration	A measure of the time between high pulse events. In forested basins, because high pulse events are rare, there are long periods of time between events. In more urbanized basins, because high pulses occur frequently, the time between high pulse events is shorter, especially during periods of the year with frequent storm events resulting in high runoff volumes in basins with large amounts of impervious surface. If high pulses constitute a significant disturbance for stream organisms, then a shorter duration between pulse events results in less time for recovery between disturbance events.
48	High Pulse Range	A measure of the length of the time period or proportion of the year, in total number of days, during which high pulse events are occurring. In more urbanized basins, there is a longer period of time between the first and last high pulse events than in more forested basins. An increase in the HPR means that more of each year is within the time period in which disturbance events are occurring and periods of the year which do not experience high pulses under forested conditions are experiencing high pulses under more urbanized conditions.

Metric Number	Metric Name & Description	Notes and Rationale for Selecting the Metric
		Timing of Flow Events
27	Date of Annual Minimum	Timing of the annual minimum related to periods of higher temperatures; possible behavioral cue.
81	Onset Of Fall Flows (1)	This statistic is redundant with the date of the 7-day minimum flow period; the assumption is that the onset of higher fall flows reflecting the start of the rainy season in PSL streams can be approximated by the end of the lowest extended low-flow period of the year.
		Rates of Change
50	Fall Rate	Rates of change may be related to ability of stream biota to move to refugia or otherwise respond to changing flows; habitat availability; potential for stranding.
51	Rise Rate	Correlated with Fall Rate. Rates of change may be related to ability of stream biota to move to refugia or otherwise respond to changing flows; habitat availability; potential for stranding.
		'Flashiness'
55	T_{Qmean} Annual	Flashiness measure; decreases with increasing EIA/TIA; related to B-IBI score;.
56	R-B Index	An increase in the daily rate of change could be a significant disturbance for organisms adapted to more stable high- or low-flow periods, and more gradual ramping up and down of flows following storm events.
76	% time above 2-year baseline	A measure of the proportion of time that flows are above a threshold that represents channel bed-moving flows under forested conditions. This metric is calculated from daily and 15 minute time-steps (see metric 78) to evaluate the effect of time-step on metric values.
78	% time above 2-year baseline	Same as #76 but using a different time-step.
		Stream Power, Geomorphically Active Flows/Storm-flow Events
79	Normalized Effective Stream Power	For fully-forested basins, this measure of stream power will be close to 1.0 and increases under increasing levels of urbanization. In our stream data set, this measure of stream power requires model data to estimate the fully-forested, 2-year flows. Alternative measures of stream power should be considered for testing that do not require model data. As stream power increases, the physical disturbance to the channel, channel substrate, and benthic organisms increases. Under increasing

Metric Number	Metric Name & Description	Notes and Rationale for Selecting the Metric
		stream power, benthic macroinvertebrates may be physically dislodged more often, subjected to increased mortality from moving bed sediments, and have reduced food availability. This is different from the standard use of stream power, which requires estimates of discharge and stream gradient.
80	Q2-Current :Q10-Fully-forested	Relative increase in magnitude of moderately frequent flow events; a measure of the magnitude of frequent disturbance events, or the intensity of disturbance.
86	Runoff Event Count	Similar to the high pulse count metrics but the runoff metrics are tied to thresholds established by baseflows rather than threshold flow values. A measure of the contribution of storm flows and the increase in this contribution with increasing urbanization.
87	Runoff Event Duration - Mean	The shorter the duration of storm flow runoff events, the greater the flashiness of the hydrograph.
88	Runoff Event Duration - Max	The shorter the duration of the maximum duration storm flow runoff events, the greater the flashiness of the hydrograph and the greater the potential flow disturbance regime. Highly correlated with #87.
	MAX/MEAN RATIOS	
60	DAY-Q MAX/MEAN	Influence of shorter-term spikes in flow relative to average flows
101	Annual Max-Hour/Mean-Daily	Influence of shorter-term spikes in flow relative to average flows

Review and Selection of Previously Developed Hydrologic Metrics

We included some hydrologic metrics developed in dam-controlled rivers to describe ecologically relevant flow changes in terms of magnitude, frequency, duration, rate of change, and timing (Richter et al. 1996, Poff et al. 1997, Olden and Poff 2003). We also included metrics developed specifically for urban or suburban PSL streams to describe flow changes resulting from increased levels of urban development, such as redistribution of runoff from baseflow to stormflow, rates of stormflow recession, increase in peak flows for small frequent flood events, and decreases in T_{Qmean} (Booth 1991, Konrad 2000, Konrad and Booth 2002, Baker et al. 2004). Where possible, we defined hydrologic metrics that we expected to be causally related to impacts on stream macroinvertebrates, such as changes in the intensity, frequency, or duration of flow related disturbances, or changes in the timing of seasonal flow events (Matthaei et al. 2004).

Seasonal vs. Annual Hydrologic Metrics and Effects of Time-Step

We developed both seasonal and annual measures to assess the effects of shorter-term, season-specific, and longer-term, annual changes in hydrology on current biological conditions, as represented by macroinvertebrate metrics. Seasonal periods were defined based on flow thresholds for low- vs. high-flow periods. Metrics defined based on flow periods include pulse counts and pulse duration during high-flow and low-flow periods of the year, and the timing of the first high-flow following the summer low-flow period (Table 4).

We also initially investigated metrics calculated with different time-steps to evaluate the effect of time-step on correlations of hydrologic metrics with percent EIA and correlations of hydrologic with biological metrics. Preliminary evaluations did not show any significant effects of time-step on the correlations reported here.

2.3.1.2 Metric Calculations

For all POI's with HSPF data, we calculated hydrologic metric values for the 1995 land cover condition using the simulated HSPF flow data for the entire 52 –year period. For POI's with streamflow gauges, we used observed streamflow data to calculate the hydrologic metrics for the 13-year period from 1989-2002. The annual mean, median, maximum, and minimum values were computed for each hydrologic metric for each POI. We used metric values from HSPF and stream gauge data to investigate (1) patterns in differences in the flow metrics across our gradient of urbanization (percent EIA), (2) differences in metric values between the two flow data sources, and (3) correlations between flow metric and biological metric values.

2.3.1.3 Observed vs. Simulated Metric Values

For POI's where we had both types of data (see Table 3), we compared the hydrologic metrics calculated with observed and simulated data. To evaluate the suitability of simulated flow data for evaluating hydrologic alteration and testing hydrology-macroinvertebrate relationships, we conducted a number of comparisons of observed and simulated data. First, we plotted hydrologic metrics against percent EIA to determine if relationships between flow metric values and impervious surface were similar for simulated and observed flow data. Second, we compared simulated vs. observed values using the Wilcoxon signed rank test (Sokal and Rohlf 1984) for each metric to determine if mean values differed significantly depending on the data type. Finally, we plotted observed vs. simulated metric values for all metrics to examine the fit between observed and simulated metrics and whether individual metrics were consistently under or over-estimated by simulated data compared to observed data.

We used comparisons of HSPF and gauge metric values as a general guideline for determining if HSPF metrics represent actual flow conditions closely enough to be used in evaluating relationships between flow measures and biological condition. If flow metrics derived from HSPF data were very different from metrics derived from stream gauge data, those metrics would not be used in evaluating correlations between flow and biology. However, these comparisons are used only as general guidelines for including metrics for the following reasons. Metrics calculated with gauge and model data are not expected to be identical due to variations in precipitation and other hydrologic processes not perfectly represented in the models. In addition, gauged flow data are generally observed over a range of land cover values reflecting changes in land use over time, and metrics calculated from these data reflect this integration. Conversely, simulated flow data are calculated from a single land cover value (i.e., 1995). Nevertheless, HSPF and gauge metric values are not completely independent. Stream gauge flow data were used to calibrate the HSPF models, and for some metrics (e.g., high pulse events), thresholds were determined using the fully forested condition from the HSPF models. We therefore used comparisons of gauge and HSPF metrics as one of the criteria, but not the only one, for selecting flow metrics to test against biology.

Finally, we investigated relationships between hydrologic and macroinvertebrate metrics using both observed and simulated hydrologic metrics, to determine if the two types of hydrologic data yield similar correlations with the biological data.

2.3.1.4 Screening of Hydrologic Metrics for Use in the Streams Analysis

To select hydrologic metrics for testing against biological metrics, we screened the list in Table 4 to develop a smaller set of priority metrics for the initial exploratory analysis. Many hydrologic metrics in the initial list are correlated and there is both statistical and ecological redundancy in the flow attributes described by these metrics (Olden and Poff 2003). We therefore screened the list of metrics for testing to satisfy one or more of the following criteria:

1. Metrics should describe aspects of flow that we expect are ecologically relevant; for example, our analyses should include attributes that describe low-flows as well as flood-flows or high pulses, or measures of duration as well as measures of frequency.

2. Metrics should be good indicators of hydrologic alterations associated with urbanization. To meet this criterion hydrologic metrics should be correlated with increasing levels of urbanization as represented by percent EIA and HSPF and stream gauge metrics should exhibit similar patterns in correlations with percent EIA.
3. Metric values should be similar when calculated using HSPF simulated data and observed gauge records.
4. Redundancy in the set of metrics should be minimized. In testing for relationships between our set of hydrologic metrics and our biological metrics, correlation among hydrologic metrics will increase the likelihood of finding spurious correlations between hydrologic and biological metrics, and will complicate interpretation of apparent hydrology-biology relationships (Olden and Poff 2003). If one or more hydrologic metrics are correlated (statistical redundancy), and if they describe similar attributes of flow (ecological redundancy), we considered excluding some of the redundant metrics from further analysis. We did not exclude hydrologic metrics that were correlated if we felt that they measured somewhat different and ecologically important aspects of flow. For example, the number of high pulses above a given threshold and the time between those pulses are correlated. However, they may describe distinctly different ecological aspects such as intensity of disturbance vs. time available for recovery from disturbance.

2.3.2 Defining and Selecting Biological Metrics

Biological metrics were defined for benthic macroinvertebrate community attributes because these metrics can be tested with existing data in PSL streams. We identified benthic macroinvertebrate metrics that we expected would be sensitive to changes in hydrology, and specifically to changes in the hydrologic disturbance regime associated with urbanization (Townsend et al. 1997, Matthaei and Townsend 2000, Matthaei et al. 2000).

Proposed biological metrics are primarily the ten B-IBI metrics and B-IBI (Kleindl 1995, Karr and Chu 1999), with a focus on the macroinvertebrate metrics thought to be more sensitive to measures of hydrologic disturbance. These metrics include long-lived taxa, clinger taxa, predators, mayfly taxa, stonefly taxa, caddisfly taxa, and dominance (Table 6). In addition to these B-IBI metrics, we initially investigated a larger number of life history and functional feeding group attributes, such as number of multivoltine taxa, number of shredder taxa, number of collector-filterer taxa, and number of collector-gatherer taxa. In these preliminary analyses, several of the ten B-IBI metrics, and most of the functional feeding group metrics did not show any clear patterns related to hydrologic metrics. Previous studies have also found that functional feeding group metrics are not good indicators of anthropogenic impacts (Karr and Chu 1999).

2.3.2.1 Selecting Biological Metrics for Testing

For the analysis discussed in this report, we focused on several metrics in addition to the ten B-IBI metrics and the B-IBI, to determine if other life-history, taxonomic, or functional group metrics are related to flow. Life-history timing metrics (e.g., taxa with restricted emergence times or seasons) are likely to be affected by flow alteration, for example, the timing of receding flows that make oviposition sites available (Peckarsky et al. 2000). However, life history information for the particular taxa in PSL streams is limited for defining these metrics. We therefore focused on metrics that we expect to be related to tolerance of an increased disturbance regime, since many of the hydrologic changes associated with urbanization constitute increases in the frequency and intensity of disturbance. We selected metrics that reflect taxa or life history attributes expected to be more resistant and/or resilient to disturbance (Matthaei et al. 2004). Invertebrate taxa were assigned attributes for the non-B-IBI metrics (e.g., conformer taxa, slow growth rate taxa) using literature values (Merritt and Cummins 1996, Morley 2000, Thorp and Covich 2001). The macroinvertebrate metrics included, and rationale for inclusion, in the final analyses are listed in Table 6.

2.4 Local Habitat Condition Measures

The relative importance of the effects of hydrologic alteration on benthic macroinvertebrates are likely to be difficult to detect because numerous other environmental factors (e.g. water quality, channel substrate, riparian buffer widths) also affect stream biota. In addition, many of these factors will be correlated with hydrologic alteration, for example, increases in peak discharges may alter channel morphology through incision or widening and modify channel substrates (Konrad and Booth 2002). To evaluate the relative influence of hydrologic alteration on biological condition, it is necessary to evaluate at least some of these additional factors as well.

Data on these other environmental factors are limited for our sites. Sampling protocols for B-IBI data sometimes include collection of habitat data for the B-IBI sampling location, but this information was not consistently collected for the samples in our data set. In-stream or local riparian habitat data from other sources also varied widely for our streams, and if available, were typically not collected at or near the B-IBI sampling sites. In several previous PSL studies local land cover measures explained more of the variation in B-IBI than sub-basin or basin land cover (Morley and Karr 2002, Booth et al. 2004). We therefore used a measure of local habitat condition at each B-IBI sampling site to evaluate the relative effects of local conditions vs. sub-basin hydrology on benthic macroinvertebrate measures.

To develop local riparian condition measures we used LANDSAT images available for the years 1995, 1998, 2000, and 2001 for the sampling locations with B-IBI data. We used percent of forest cover as a measure of the relative condition of the riparian area immediately adjacent to each B-IBI sampling location because forested riparian zones are associated with higher quality habitat conditions for stream macroinvertebrates (Hershey and Lamberti 1998). The total percent non-urban forest cover within a 100 meter and 300 meter radius of each B-IBI sampling location was estimated for each year with

LANDSAT data. We therefore had three scales of land cover data for each B-IBI sampling location: sub-basin percent EIA, percent forested within a 300m radius, and percent forested within a 100m radius.

2.5 Data Analyses

Existing data sets available to us were not specifically designed to test hypotheses about relationships between flow regimes and benthic macroinvertebrate community attributes. We therefore emphasized exploratory statistical analyses:

- As a critical first step in evaluating patterns in relationships between flow and biology in this data set,
- To provide results of the exploratory analyses as preliminary recommendations that can immediately inform management decisions and actions, and
- To provide insights and guidance for development of the stream assessment tools and method, and future studies of the effects of flow alteration, in terms of data collection and analysis requirements, experimental design, and developing predictive hypotheses.

We used a combination of graphical visualization, bivariate correlations, and descriptive statistical approaches to explore our data sets for patterns in hydrologic alteration, and for relationships between hydrologic and macroinvertebrate metrics. Inferences drawn from these exploratory tests can (1) identify relationships between flow and biology that suggest predictive hypotheses for testing, and (2) identify metrics, which are informative about biologically relevant flow changes in PSL urban streams, and can be used to evaluate flow alteration and provide guidance on likely biological responses.

2.5.1 Graphical Inspection and Bivariate Plots

Initial comparisons used the graphical approach and visual inspection recommended by Karr (Karr 1998, Karr and Chu 1999) as a first step in examining patterns in the hydrologic and biological data and identifying potential relationships between hydrologic and biological conditions. We expected that current biological condition, as measured by macroinvertebrate metrics, would be correlated with current hydrologic metric values. We used Spearman's correlation coefficient (r_s) to determine which metric pairs showed potentially strong and significant correlations (Sokal and Rohlf 1984). Significant correlations were then evaluated to identify hydrologic and biological metrics for use in developing stream assessment tools and management guidance.

We also used the bi-variate plots and a graphical approach to explore the effects of B-IBI data source, sample size, stream order, and local riparian condition on hydrology-biology relationships.

Table 6. Benthic Macroinvertebrate Metrics Screened for Testing, Metric Definition, and Rationale Linking Biological Metrics with Flow Alteration.

Metric Name	Metric Definition	Rationale for Metric – Proposed Link to Hydrology
	Composition Measures	
% Chironomids	Family = Chironomidae; Order = Diptera. Percent of the total number of Dipteran individuals that are Chironomids.	Chironomids tend to be small, tolerant of disturbance, with rapid population growth rates and should be able to tolerate and recover from disturbance more easily than other Dipteran taxa; as disturbance increases or disturbance regime changes, the relative % of Chironomids among Dipterans may increase.
% Baetis individuals; (% of individuals that are Baetidae)	Genus = Baetis. Percent of all individuals that are in the family Baetidae.	Within the Ephemeroptera, Baetids as a group have highly mobile larvae, short-lived but widely dispersing adults, short life-cycles and rapid population growth rates. These taxa should be more tolerant of and more able to recover from increased disturbance than longer-lived, less mobile, and more slowly reproducing taxa.
Total Abundance	Total number of individuals in the sample	As hydrologic disturbance increases, and at very high rates of disturbance, the total number of individuals may decrease because habitat complexity and physical disturbance reduce the overall suitability of habitat to support larger numbers of individuals.
	Feeding Measures	

Metric Name	Metric Definition	Rationale for Metric – Proposed Link to Hydrology
# Obligate Shredder Taxa	Functional Feeding Group = SH (include only those that are 100% SH). Total number of taxa that are SH	Shredder taxa should be sensitive to greatly increased frequencies of high pulses and longer periods of the year with high pulses (e.g., late summer/early fall) which may increase export rates of CPOM[10] and decrease residence times of CPOM, both of which may reduce food availability and quality.
% Abundance Collector Filterers	Functional Feeding Group = CF (include only those that are 100% CF). Percent of total number of individuals that are CF	Collector filterers should be relatively tolerant of higher flows and increased frequency of higher flows; many are clingers and tolerate higher flows and can filter food at greater rates under higher velocities.
Ratio of Collector Gatherers/Collector Filterers (# taxa)	Functional Feeding Group = CG OR CF. Ratio of # CG taxa to # CF taxa.	Collector gatherers should be relatively less tolerant of increased peak flows and frequencies of peak flows than filterers (see above) and the ratio of CG/CF is expected to decrease is hydrologic disturbance increases.
# Predator Taxa	Functional Feeding Group = PR. Total number of taxa that are predators.	Predator taxa tend to be more long-lived, with longer reproductive cycles than other taxa and may not be able to recover as quickly from increased frequency or magnitude of disturbance.

Life History Measures

[10] Coarse particulate organic matter

Metric Name	Metric Definition	Rationale for Metric – Proposed Link to Hydrology
# Uni-voltine+Semi-voltine Taxa	Number of taxa that are UV (include only those that are 100% UV - univoltine) + SM (include all that are at least 50% SM - semivoltine).	These taxa represent the more slowly reproducing taxa and in general would be expected to have lower population growth rates than multi-voltine taxa. Taxa with longer generation times and lower population growth rates may not be able to recover as readily from disturbance as taxa with shorter generation times and higher potential population growth rates.
# Large/Longer Developmental Time Taxa (# taxa that are Nemouridae, Chloroperlidae, Leuctridae, Ephemerellidae, Heptageniidae, Pteronarcys)	Family = Nemouridae, Chloroperlidae, Leuctridae, Ephemerllidae, Heptageniidae, Pteronarcyidae. Total number of discrete taxa in these families.	These taxa take longer to complete life cycles, these taxa also tend to have larger body sizes; this metric is very similar to the long-lived taxa metric. Taxa that take longer to complete development should be more sensitive to increased disturbance and to the change in timing of flow events linked to life history stages.
# Conformer Taxa (# of taxa that are in Families: Rhyacophilidae, Blephariceridae, Heptageniidae)	Family = Rhyacophilidae, Blephariceridae, Heptageniidae. Percent of total number of individuals that are in these families.	Conformer taxa require moving, well oxygenated water for respiration; these taxa should be more sensitive to prolonged low flows or increased flashiness and low pulses vs. stable higher flows.
# MV Taxa	Number of taxa that are MV (include taxa that are 75% or more MV)	MV taxa have shorter life cycles and higher reproductive rates. These taxa should be able to recover more quickly from disturbance than uni- or semi-voltine taxa and should be less affected by increases in hydrologic disturbance regime.
	B-IBI METRICS	
# Ephemeroptera taxa	Total number of Ephemeroptera (mayfly) taxa	
# Plecoptera taxa	Total number of Plecoptera (stonefly) taxa	

Metric Name	Metric Definition	Rationale for Metric – Proposed Link to Hydrology
# Trichoptera taxa	Total number of Trichoptera (caddisfly) taxa	
% Predators	% of all individuals that are predators	
# Clinger Taxa	Total number of taxa that are clingers	
# Long-lived taxa	Number of long-lived taxa	
# Intolerant Taxa	Number of intolerant taxa (sediment intolerant)	
% Dominant Three	% of all individuals that are in the three most abundant taxa	
% Tolerant Taxa	% of all individuals in tolerant taxa (to organic pollutants)	
Total Taxa	Total # of taxa in sample	
B-IBI Score	Multi-metric score combining the 10-metric scores	

2.5.2 Effects of Local Riparian Conditions vs. Sub-Basin Hydrology

To determine if variability in other environmental factors explains some of the scatter in our bi-variate relationships, we evaluated the effects of local riparian condition on the relationships between hydrologic and biological metrics. Bi-variate scatter plots of biological metrics and hydrologic metrics frequently exhibit a *factor ceiling* or limit pattern similar to that observed between B-IBI and measures of urbanization (Booth et al. 2004). If hydrology is the most important limiting factor, then the hydrologic metric value will determine the maximum (or minimum) biological metric value and the scatter of biological metric values below (or above) the ceiling is influenced or limited by other factors, such as local land cover conditions. If local land cover explains some or most of the variation under the factor ceiling, then examining patterns in local riparian cover may explain more of the patterns in relationship between hydrologic and biological metrics than flow and biology alone.

To determine if the pattern of relationship between hydrologic and biological metrics changes depending on local land cover conditions, we visually examined patterns in local riparian condition in the scatter plots of hydrologic metrics and biological metrics.

2.5.3 Differences in Hydrology between Sites Grouped by Biological Similarity

We asked whether sites with similar biological condition (as defined by ranges of the B-IBI) were significantly different in terms of hydrologic metric values. Because the flow metrics do not meet the requirements of parametric tests (i.e., normal distribution), we used non-parametric rank tests to evaluate differences in hydrologic metrics among biological groups (Kruskal Wallis, Sokal and Rohlf 1984). The Kruskal-Wallis test is analogous to a one-way analysis of variance (ANOVA), but rather than determining if mean hydrologic metric values differ among the biological groups, the non-parametric test determines if relative rankings of metric values are distributed randomly across the biological groups (Sokal and Rohlf 1984). Sites from the stream data set were grouped into four ‘biological condition’ categories based on B-IBI for very poor, poor, fair, and good biological condition (May et al. 1997, Morley and Karr 2002). Group 1 sites have B-IBI between 10 and 16 (very poor), Group 2 sites are between 18 and 26 (poor), Group 3 sites are between 28 and 36 (fair), and Group 4 sites have B-IBI greater than 38 (good)

3.0 RESULTS

3.1 Change in Hydrologic Metrics Along the Urbanization Gradient

A number of hydrologic metrics are correlated with percent EIA. Patterns are similar for both stream gauge and HSPF flow data. When the mean values for all POI's are plotted against percent EIA, the number of high and low pulse events, number of reversals, low and high pulse range, rise count, and portion of the year that flows are above the 2-year mean flow, all increase as percent EIA increases (Figures 4 and 5). Mean values for T_{Qmean} and the number of days between high and low pulse events decrease with increasing percent EIA, and the onset of fall flows is earlier (Figures 4 and 5). For those metrics calculated only from HSPF flow data, normalized effective stream power, Q2:Q10, fall count, and number of runoff events increase with increasing percent EIA (Figure 5). The magnitude of the change in flow metrics across the gradient of percent EIA varies for different metrics and depends on whether metrics were calculated from stream gauge or HSPF data.

Correlation coefficients are similar for stream gauge and HSPF data for most of the hydrologic metrics, and the correlations are in the direction expected given the predicted effects of percent EIA on runoff and stream flow (Table 7). Correlations were considered to be moderately strong if $r>0.4$ and $p<0.001$. The strongest correlations with percent EIA for both hydrologic data sets include the low and high pulse metrics – event count, duration – or days between events, and range – or portion of the year with pulse events; fall rate, rise count, T_{Qmean}, percent of time above the 2-yr mean flow, date of the onset of fall flows, and number of flow reversals. Two of the hydrologic metrics showed strong correlations with percent EIA when stream gauge data were used, but not with HSPF data (1-day annual maxima and rise rate). Three metrics showed strong correlations with percent EIA with HSPF data but not with stream gauge data (date of annual minima, R-B Index, daily maximum Q to annual mean Q). Normalized effective stream power, Q2:Q10, hourly annual maxima, runoff event count metrics, and hourly maxima to annual mean ratio were only calculated with HSPF data and all had strong correlations with percent EIA (Table 7)

3.1.1 High and Low Pulse Events

The change in number of high and low pulses is similar across the gradient of EIA and also similar for stream gauge and HSPF flow data (Figures 4 and 5). The range in high and low pulse event values is from 5-6 per year (<1% EIA) to about 20-25 per year (24% EIA). The relationship between percent EIA and days between pulse events is different for pulses with high-flow thresholds and low-flow thresholds. The time between low pulses is about 32 days shorter when percent EIA is >20 compared to sites with percent EIA <1 (Figures 4 and 5). The time between high pulses is about 8 days shorter across the same gradient of EIA (Figures 4 and 5). The time between pulses with low-flow thresholds is more strongly affected by urbanization than for pulses with high-flow thresholds.

The portion of the year with high pulses increases by about 175 days (stream gauge data) and by about 150 days (HSPF flow data) across the urbanization gradient from <1% to >20% EIA. The portion of the year with low pulses increases slightly less, by about 140 days, across the gradient of increasing EIA.

3.1.2 Timing of the Onset of Fall Flows

In our set of streams, the timing of the onset of fall flows changes across the gradient of urbanization. The mean date of fall flows (mean Julian date) decreases with increasing percent EIA for both HSPF and stream gauge metrics (see Figures 4 and 5). Fall flows occur significantly earlier in sub-basins with higher percent EIA. The onset of fall flows occurs about 35 days (HSPF flow data) to about 55 days (stream gauge data) earlier in sub-basins with >20% EIA compared to sub-basins with <1% EIA.

3.1.3 Geomorphically Active Flow Metrics

Flow metrics that represent a measure of the change in the frequency or magnitude of flows that have the potential to physically affect channel form or move channel bed materials, all increased with increasing percent EIA (Figures 4 and 5). Normalized effective stream power and Q2:Q10 showed the greatest increase across our gradient of EIA. Normalized effective stream power increased gradually from 1 to 1.5 as EIA increased from <1% to about 7-8%. Between an EIA of 8% to 20%, effective stream power increased from 2.5 to 4 (Figure 5). Similarly, the ratio of the current 2-year to forested 10-year flow rate (Q2:Q10) is between 0.25 and 0.65, and does not increase significantly between about 1% to about 5% EIA. As the EIA increases from 7% to 20%, the current 2-year flow rate increased from about equal, to 2.5 times greater than, the historic or forested 10-year flow rate (Figure 5).

3.1.4 Differences Among Stream Sub-Basins

Several of the plots of HSPF model metrics against percent EIA show that the streams in our set fall into two distinct groups (Figure 5). Streams in Issaquah sub-basins tend to group separately and show distinct patterns in relation to percent EIA compared most of the other streams for some of the hydrologic metrics. For example, for the number of rises (10% rule) and the number of days between the first and last high pulse events, Issaquah basin streams tend to have higher values than expected for a given percent EIA (Figure 5).

Although all the streams used in this analysis were restricted to 2nd to 4th order, the 2nd order tributaries in the Issaquah basin are still slightly higher in elevation, and greater proportions of the basins are underlain by till soils or bedrock than the other streams in our data set. This stream system, and especially the smaller tributaries, tend to be flashier naturally than other streams in the data set with a higher percentages of outwash soils in the basin.

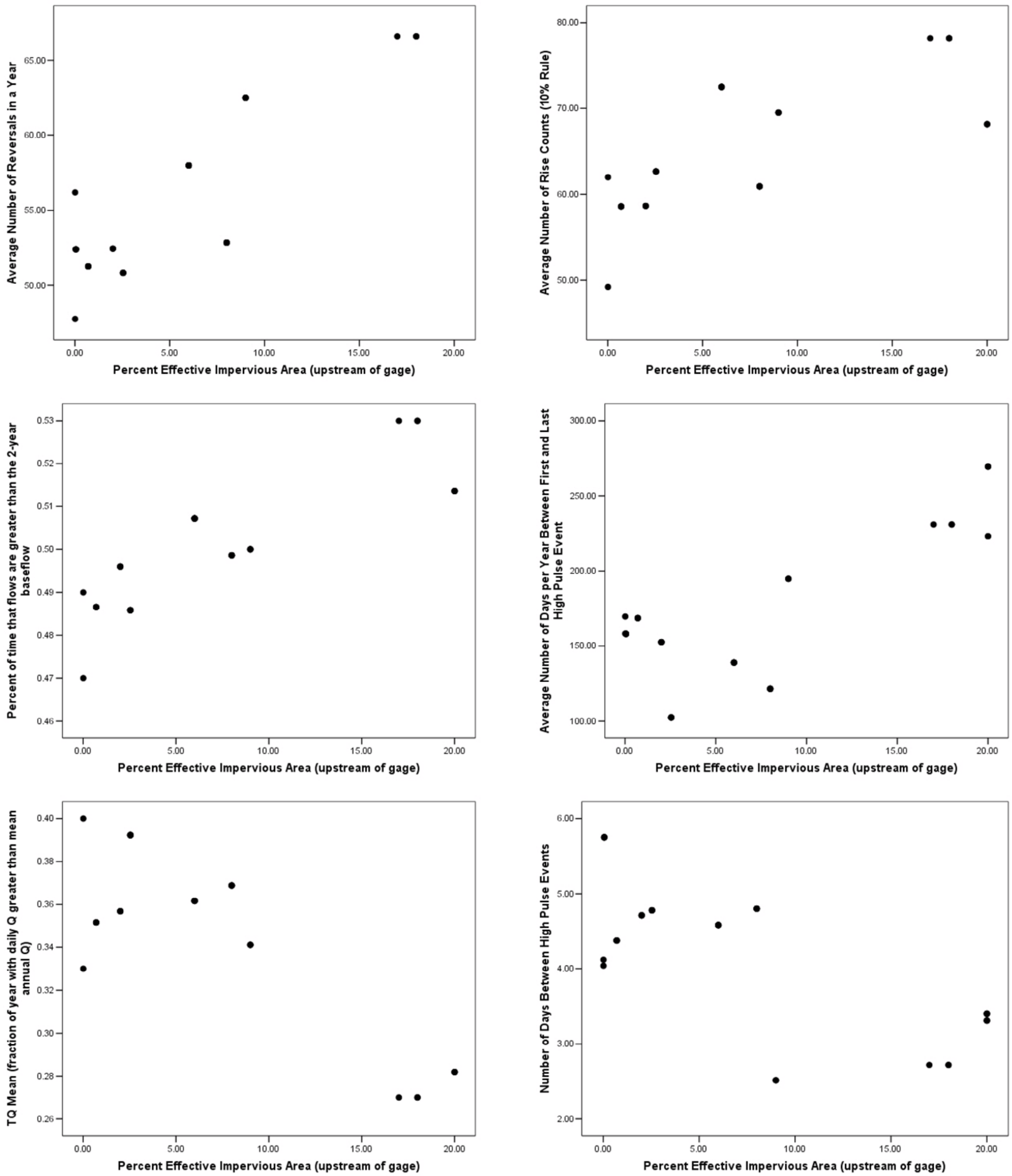


Figure 4. Gauge flow metrics plotted against percent EIA.

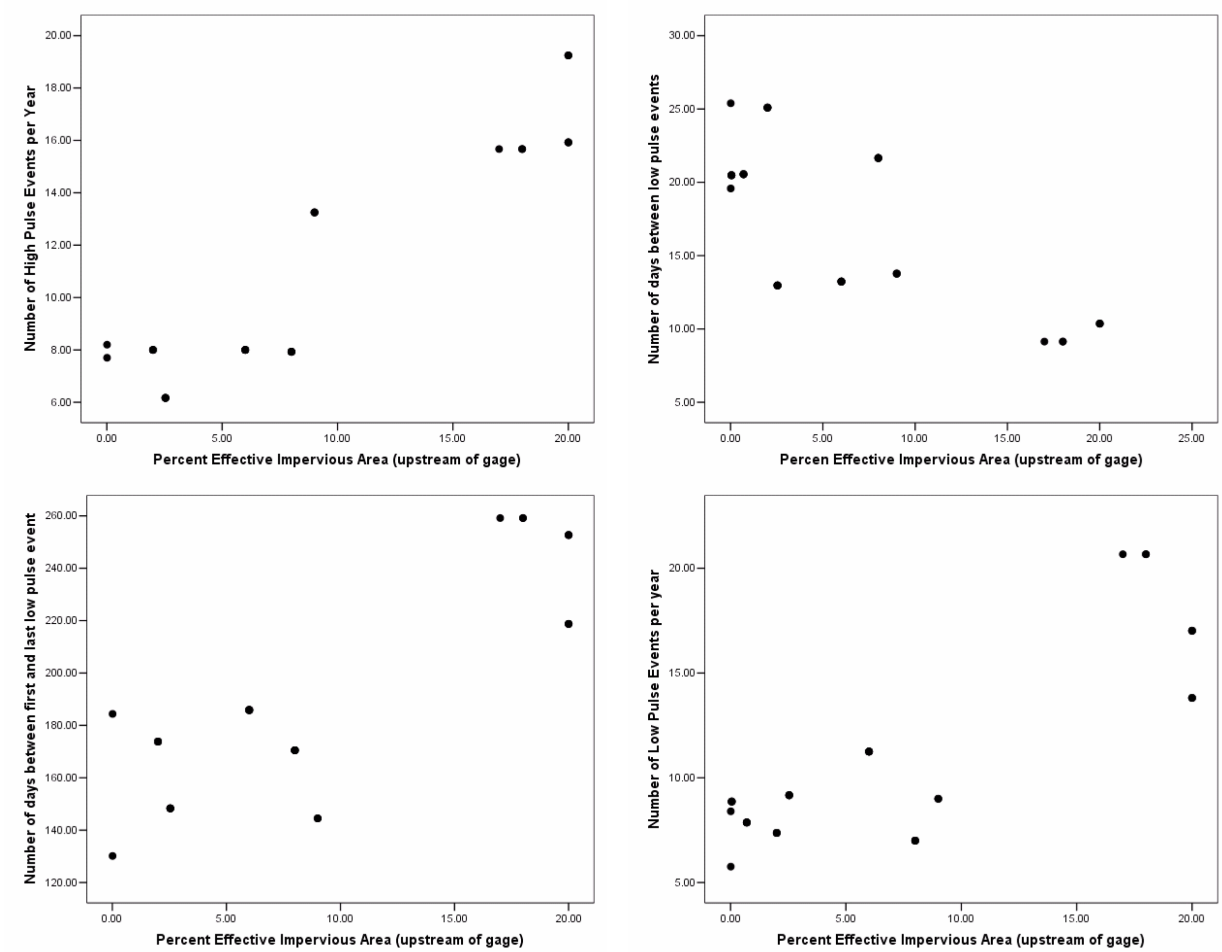


Figure 4. Gauge flow metrics plotted against percent EIA.

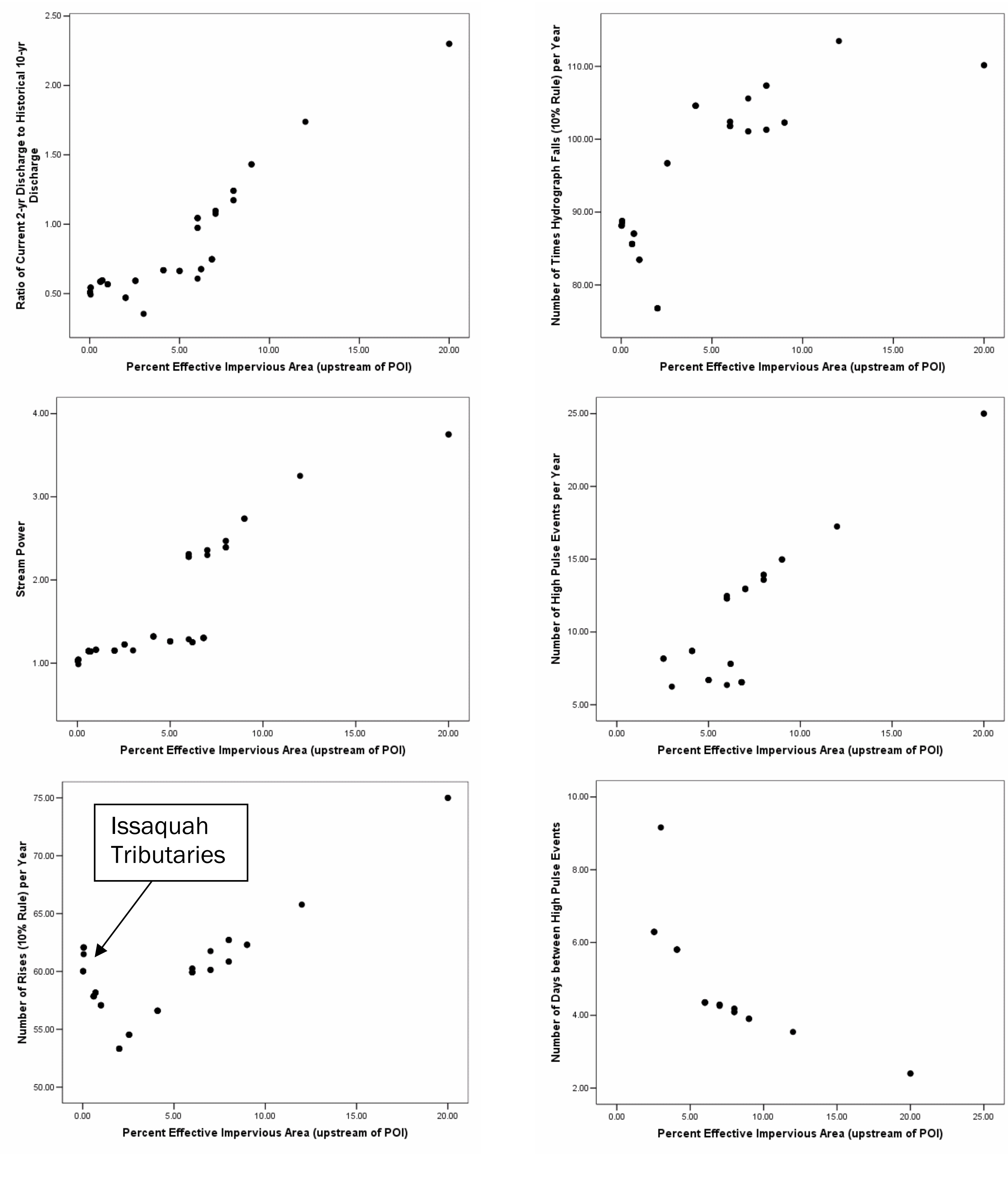


Figure 5. HSPF flow metrics plotted against percent EIA.

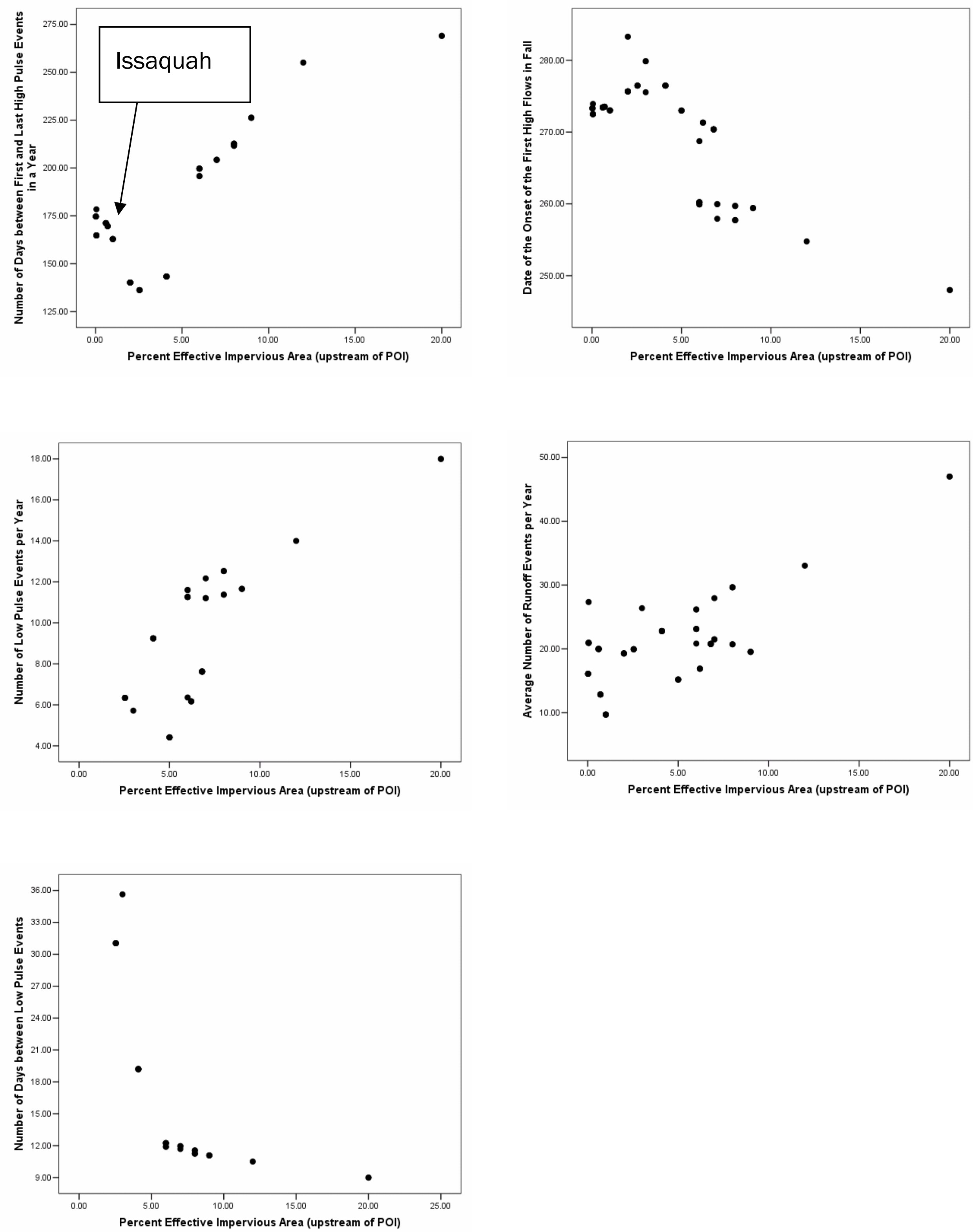


Figure 5. HSPF flow metrics plotted against percent EIA.

Table 7. Correlations between Hydrologic Metrics and Percent Effective Impervious Area (%EIA) for both Gauge and HSPF Flow Data.

METRIC NAME	OBSERVED FLOW DATA (n = 11 POI's)		MODEL FLOW DATA (n = 38 POI's)	
	Spearman's Correlation Coefficient	p value	Spearman's Correlation Coefficient	p value
7-Day Annual Minima	-.449	.001	-.101	.257
1-Day Annual Maxima	-.611[11]	<.001	-.187	.112
Date of Annual Minimum	-.374	.011	-.784	<.001
Date of Annual Maximum	-.184	.225	-.432	>002
Low Pulse Count	**.807**[12]	**<.001**	**.647**	**<.001**
Low Pulse Duration	**-.670**	**<.001**	**-.517**	**<.001**
Low Pulse Range	**.829**	**<.001**	**.488**	**<.001**
High Pulse Count	**.925**	**<.001**	**.845**	**<.001**
High Pulse Duration	**-.726**	**<.001**	**-.528**	**<.001**
High Pulse Range	**.753**	**<.001**	**.757**	**<.001**
Fall Rate[13]	**.481**	**.001**	**.653**	**<.001**
Rise Rate	.530	<.001	.200	.096
Fall Count (0.1 Rule)	.335	.024	.333	.014
Rise Count (0.1 Rule)	**.663**	**<.001**	**.734**	**<.001**
T-Qmean Annual	**-.825**	**<.001**	**-.773**	**<.001**
R-B Index	.297	.048	.839	<.001
Hourly Annual MAX	NA[14]	NA	.575	<.001
DAY-Q MAX/MEAN	.282	.060	.505	<.001
% time above 2-year baseline	**.844**	**<.001**	**.862**	**<.001**
Stream Power - Relative to Baseline	NA	NA	.818	<.001
Q2:Q10	NA	NA	.926	<.001
Onset of Fall Flows (1)	**-.886**	**<.001**	**-.797**	**<.001**
Baseflow Minimum Flow	NA	NA	-.106	.246
Runoff Event Count	NA	NA	.774	<.001
Runoff Event Duration - Mean	NA	NA	-.573	<.001
Runoff Event Duration - Max	NA	NA	-.342	.012
Flow Reversals	**.842**	**<.001**	**.635**	**<.001**
Annual Max-Hour/Mean-Daily	NA	NA	.844	<.001

[11] Correlations highlighted in grey are significant and moderate to strong (r > 0.4 and p <0.001) with one data source but not both.

[12] Correlations in bold are moderate to strong, r > 0.4 and p <0.001, with both data sources.

[13] Absolute value of the fall rate; the greater the magnitude of the fall rate the more rapidly recession takes place. Absolute value of fall rate is positively correlated with %EIA.

[14] NA – metric not calculated with observed stream flow data.

3.2 Effects of Data Source on Hydrologic Metrics

3.2.1 Similarity of Stream Gauge and HSPF Hydrographs

Hydrographs generated from mean daily flows using stream gauge and HSPF data for the same basin under the same precipitation conditions show generally similar flow patterns; however, HSPF hydrographs do not precisely match the stream gauge hydrographs (Figure 6a-b). General patterns are similar in terms of the number of storm peaks, duration of storm peaks, and magnitude of summer baseflows. However, some individual storm events are not captured, or are over- or under-estimated by the HSPF models (Figure 6a-b).

3.2.2 Stream Gauge and HSPF Hydrologic Metric Values

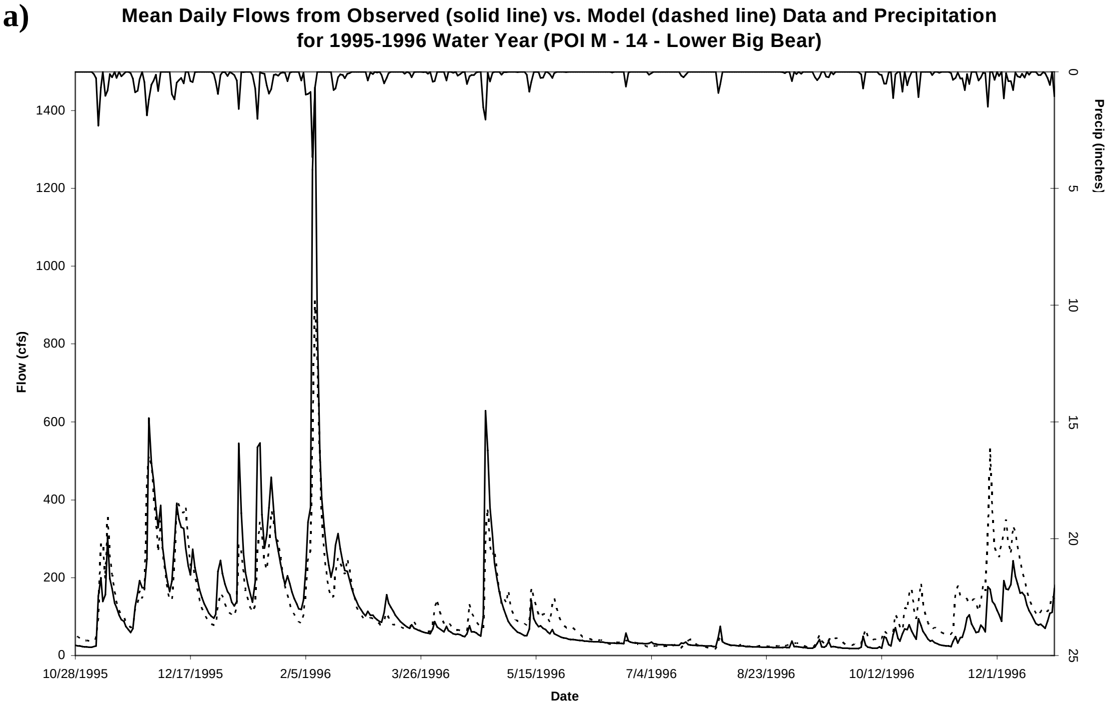
Hydrologic metric median values and ranges calculated with both stream gauge and HSPF data are similar for some flow metrics but not for others (Figure 7). When data from all POI's in the seven stream basins are included, non-parametric comparisons of metrics from both data sources show that for about half of the metrics evaluated, stream gauge and HSPF metric values are significantly different (Table 8). Individual metric values are highly variable with both data sources (Table 8).

Individual sub-basins may differ in the degree to which HSPF simulated flows match observed stream flows and therefore metrics calculated from the two data sources may be more similar for some POI's than for others. When paired HSPF and stream gauge metric values are plotted for all POI's, some metrics show a match close to 1:1, while other metrics clearly differ depending on data source (Figure 8). For the models used with our stream set, HSPF data result in consistently greater values relative to stream gauge data for several metrics, including the number of days between the first and last low pulse, R-B index, the magnitude of the daily maximum flow to mean daily flow. For other metrics, including fall count, rise count, and T_{Qmean}, HSPF data result in consistently lower metric values relative to stream gauge data (Figure 8).

3.2.2.1 Correlations Among Hydrologic Metrics

To screen hydrologic metrics for testing against biological metrics we examined correlations among the set of flow metrics. Most of the high and low pulse metrics, rise and fall counts, T_{Qmean}, R-B Index, and number of reversals are all correlated (Appendix A;Table A-1). In contrast, the date of the onset of fall flows and the portion of the year with flows above the mean 2-year flow are not correlated, or not as strongly correlated, with measures such as T_{Qmean}, rise and fall rates, rise and fall counts, and low or high pulse duration and range (Appendix A; Table A-2).

a)



b)

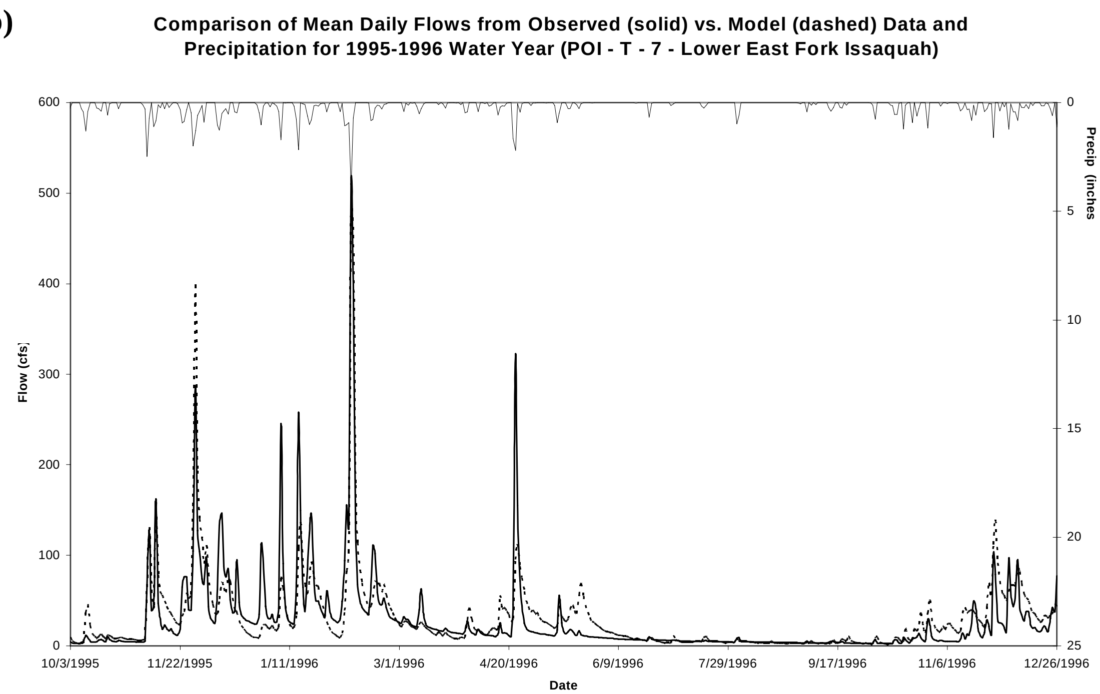


Figure 6. Comparison of HSPF and stream gauge hydrographs for a predominantly forested and a highly urbanized basin.

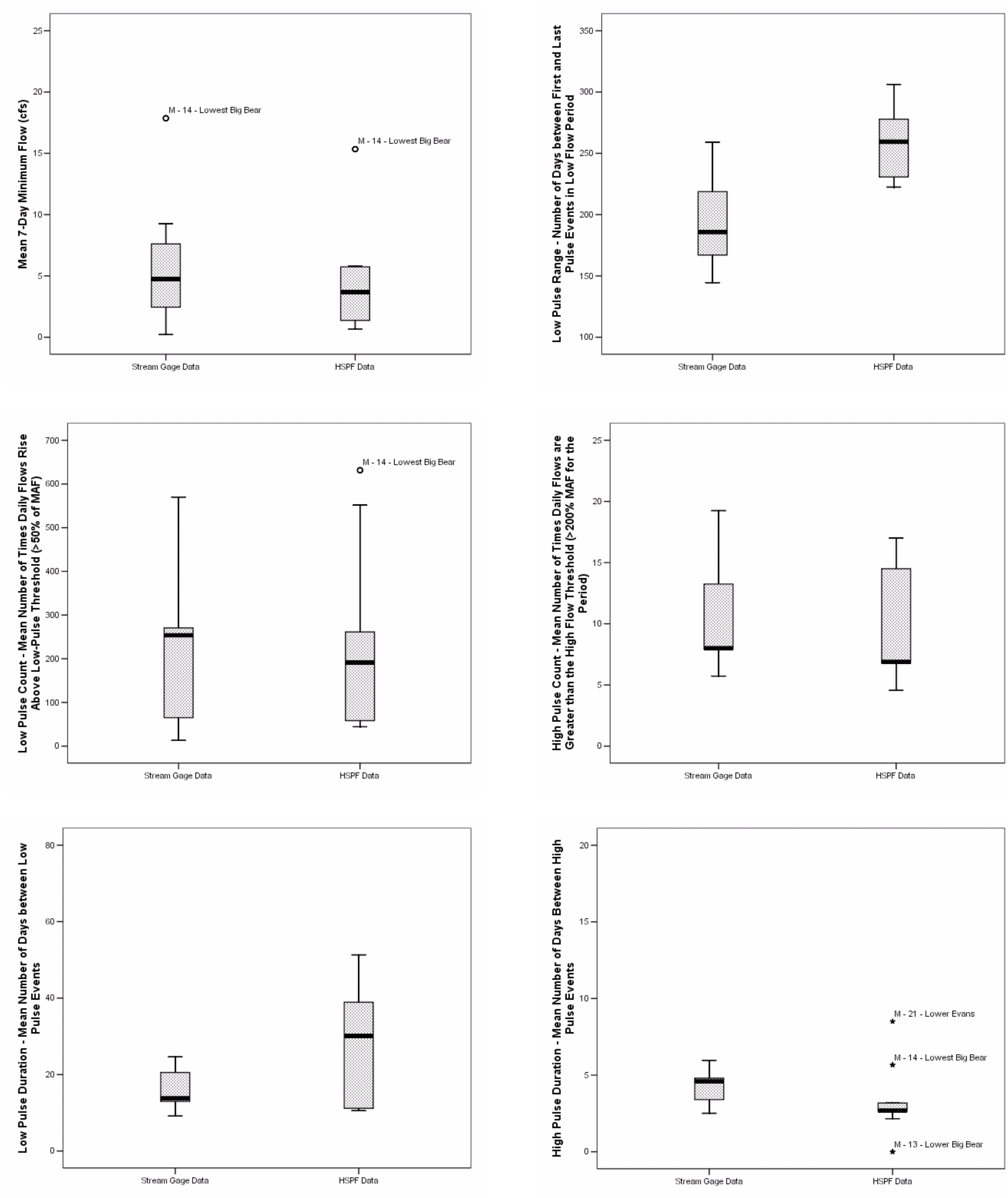


Figure 7. Comparison of flow metric values calculated with stream gauge and HSPF data.

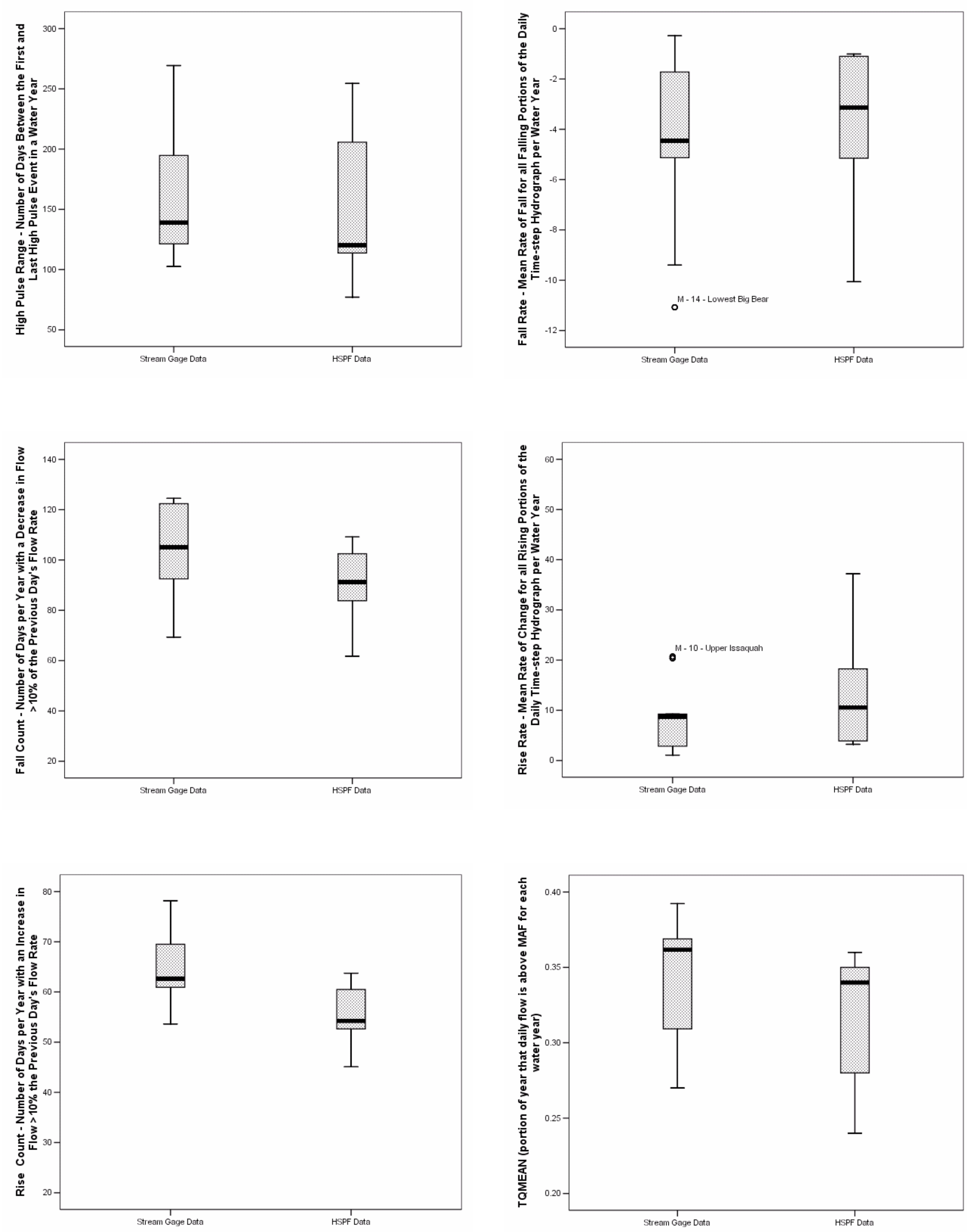


Figure 7. Comparison of flow metric values calculated with stream gauge and HSPF data.

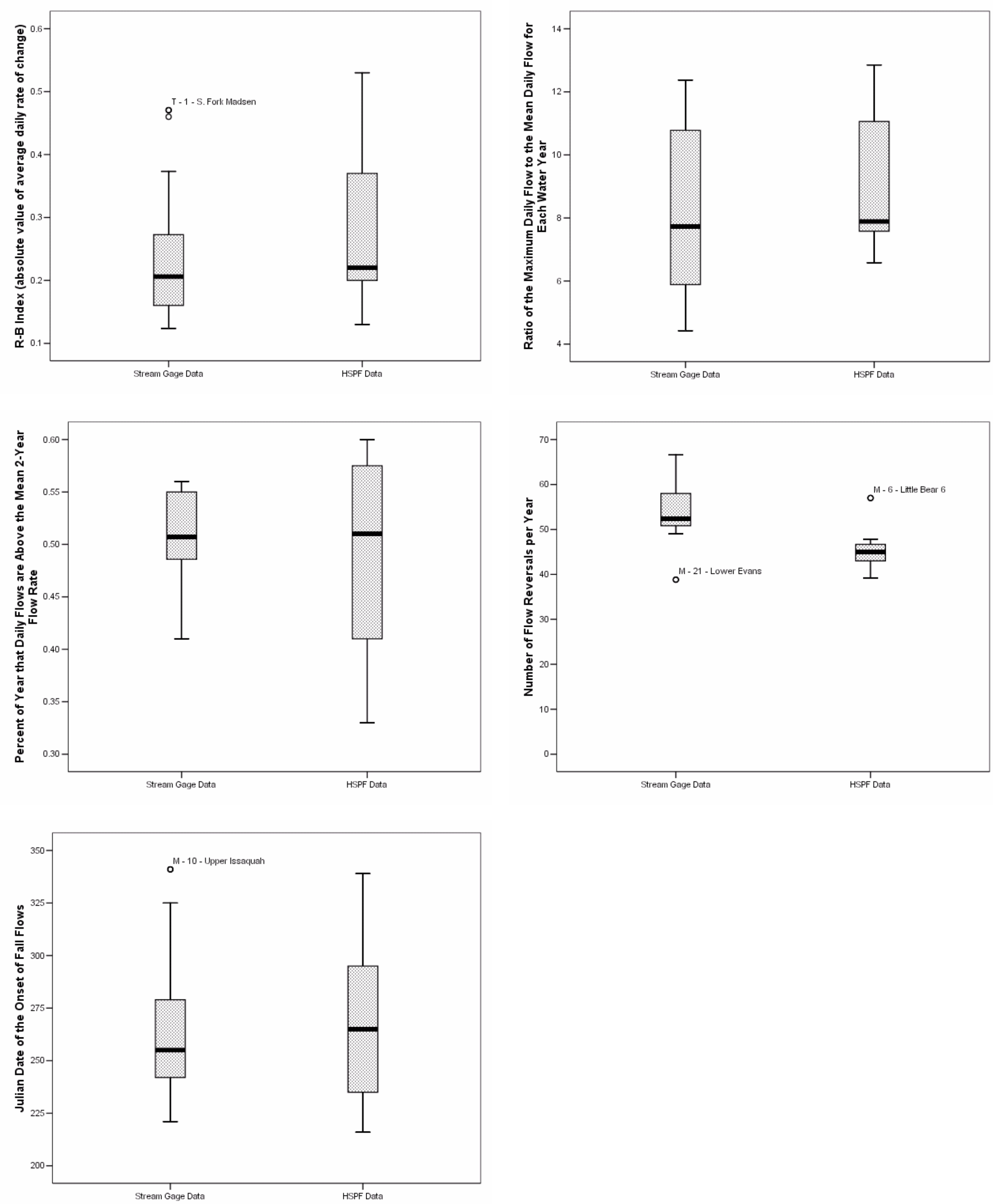


Figure 7. Comparison of flow metric values calculated with stream gauge and HSPF data.

Table 8. Comparison of Metric Values Calculated with Stream Gauge and HSPF Data.

Hydrological Metric	N*	Mean	Std. Deviation	Minimum	Maximum
7-day Minimum	**11**	**6.7913**	**6.31537**	**.21**	**22.13**
HSPF 7daymin	38	4.8569	5.14012	.65	15.34
1-day Maximum[15]	**11**	**213.3647**	**203.01037**	**13.22**	**669.07**
HSPF1daymax	38	205.0097	207.22705	44.44	631.53
Low Pulse Count	**11**	**10.3437**	**3.79009**	**5.76**	**20.67**
HSPFLPC	38	10.0717	4.59788	4.33	19.50
Low Pulse Duration	**11**	**15.7627**	**5.10139**	**9.14**	**25.39**
HSPFLPD	38	25.4666	15.90354	10.55	51.31
Low Pulse Range	**11**	**181.6773**	**36.05823**	**130.15**	**259.17**
HSPFLPR	38	257.5334	30.19788	222.43	306.25
High Pulse Count	**11**	**9.8036**	**4.02739**	**5.73**	**19.25**
HSPFHPC	38	10.6895	4.53013	4.55	17.92
High Pulse Duration	**11**	**4.2536**	**.97676**	**2.52**	**5.96**
HSPFHPD	38	3.2707	2.53771	.00	8.50
High Pulse Range	**11**	**158.8646**	**54.33889**	**102.50**	**269.40**
HSPF HPR	38	141.6159	56.06348	77.17	254.50
Fall Rate	**11**	**-4.4446**	**3.81575**	**-12.57**	**-.28**
HSPFFR	38	-3.3845	2.94722	-9.08	-1.01
Rise Rate	**11**	**8.4626**	**7.57202**	**1.08**	**30.90**
HSPFRR	38	10.7741	10.05921	3.22	31.52
Fall Count	**11**	**101.8774**	**18.66547**	**66.39**	**124.51**
HSPFFC	38	94.3341	13.41587	61.73	109.17
Rise Count	**11**	**64.6430**	**6.76294**	**49.17**	**78.17**
HSPFRC	38	55.4445	5.99341	45.09	63.75
Tqmean	**11**	**.3511**	**.03918**	**.27**	**.40**
HSPFTqmean	38	.3286	.03292	.24	.36
Rbindex	**11**	**.2372**	**.11578**	**.12**	**.47**
HSPFRbindex	38	.2617	.10902	.13	.53
dayQmax.mean	**11**	**7.6427**	**2.66924**	**4.42**	**12.37**
HSPFQmax.mean	38	8.3021	1.72397	6.58	12.01
%above2yr	**11**	**.5016**	**.01550**	**.47**	**.53**
HSPFabove2yr	38	.3569	.07829	.21	.43
OnsetFall	**11**	**254.87**	**28.208**	**221**	**345**
HSPFonset	38	252.3448	24.80823	216.00	295.00
Reversals	**11**	**52.7993**	**6.71058**	**38.82**	**66.58**
HSPF reversals	38	45.7652	4.67700	39.18	57.00

* HSPF Data Set Does Not Include Upper Rock or Taylor – no calibrated models were available to correspond to these gauge sites

[15] Highlighted rows: gauge metric values and HSPF metric values are **not** significantly different (Wilcoxon Signed Ranks test)

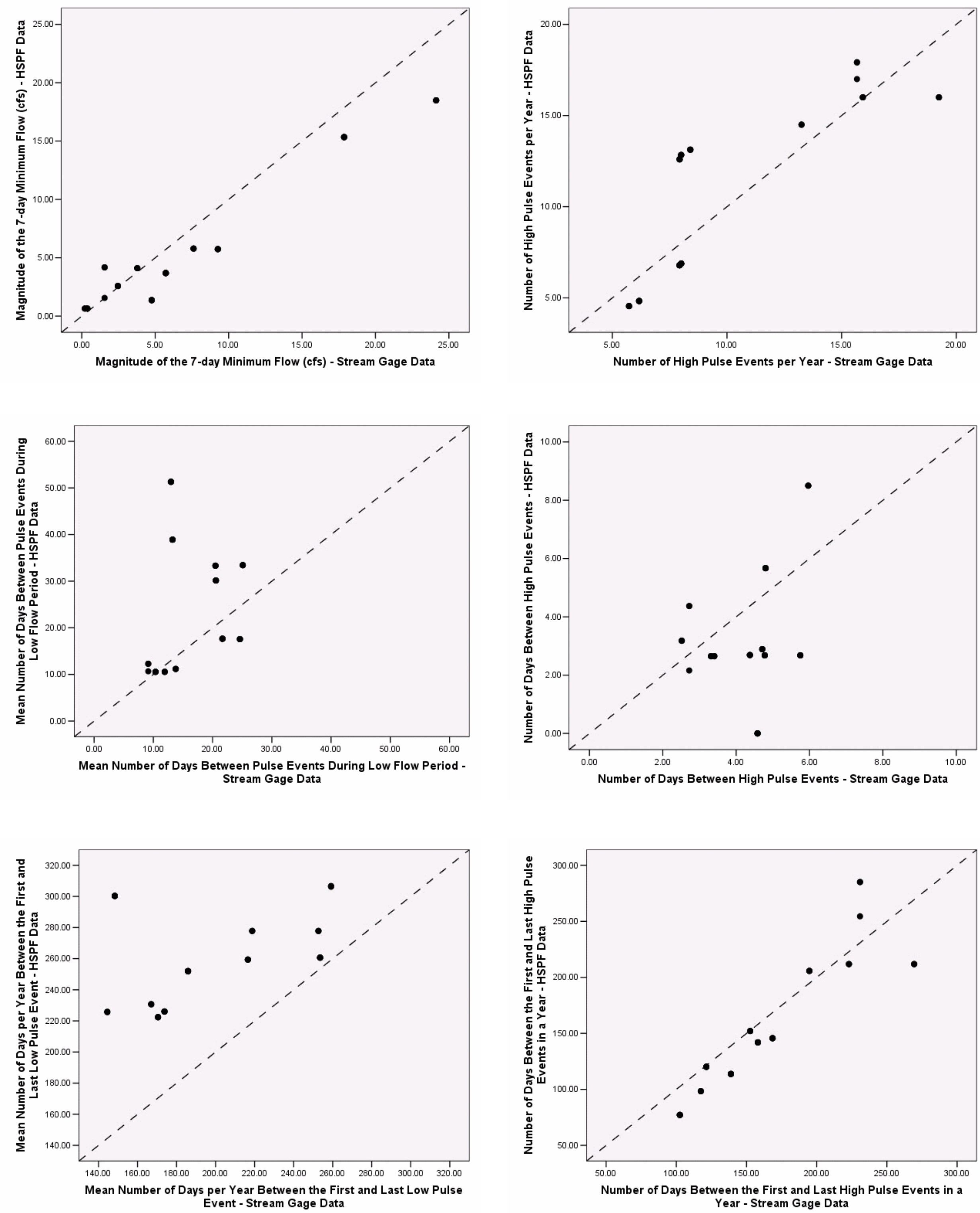


Figure 8. HSPF metric values plotted against stream gauge metric values for each POI. Dashed line represents a 1:1 ratio of HSFP to stream gauge metric values.

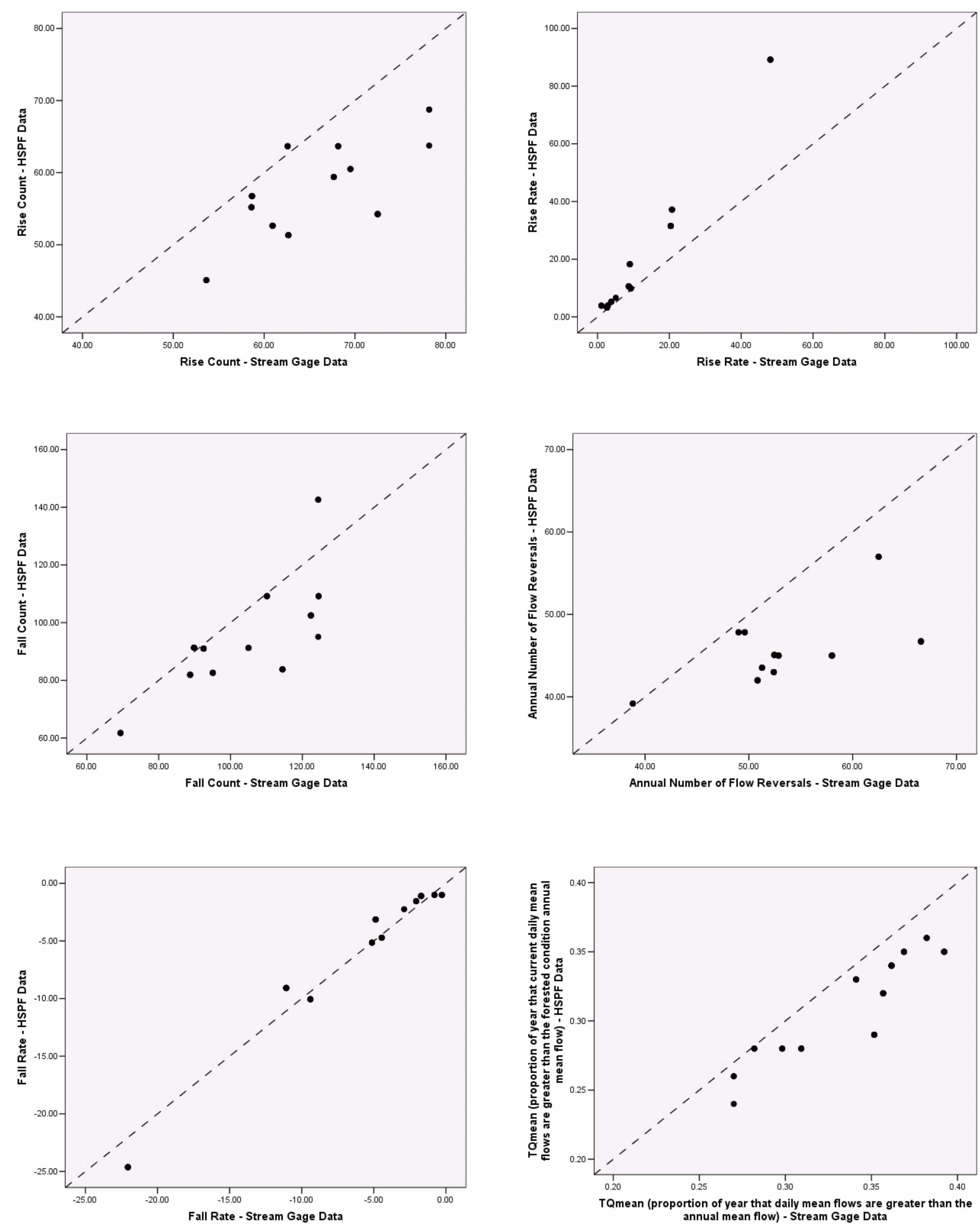
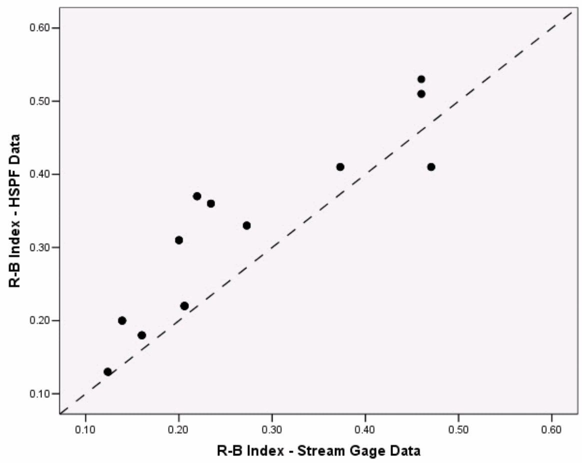
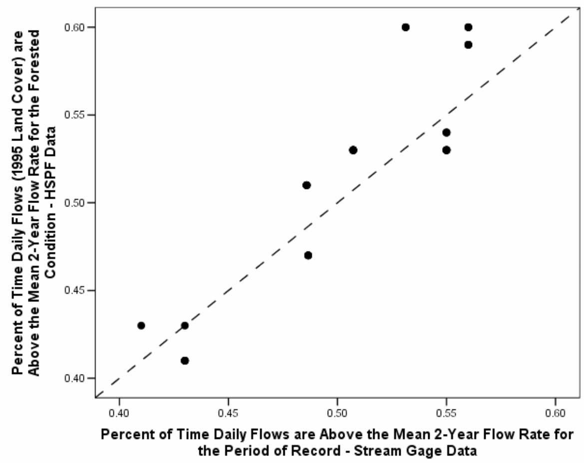


Figure 8. HSPF metric values plotted against stream gauge metric values for each POI. Dashed line represents a 1:1 ratio of HSPF to stream gauge metric values.





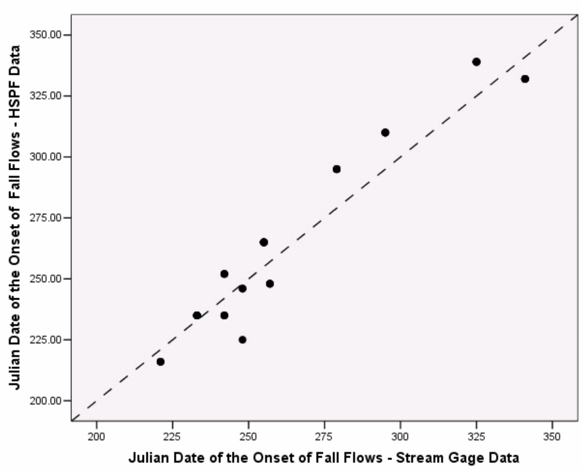


Figure 8. HSPF metric values plotted against stream gauge metric values for each POI. Dashed line represents a 1:1 ratio of HSPF to stream gauge metric values.

3.2.3 Metrics Meeting the Screening Criteria

Based on our screening criteria for hydrologic metrics and the HSPF/stream gauge comparisons, Table 9 lists metrics selected for testing with biological data and the relative level of uncertainty associated with use of HSPF data for each metric. This list represents a sub-set of the metrics that:

- includes metrics correlated with percent EIA,
- minimizes redundancy among the flow metrics,
- retains a set of metrics that capture different aspects of flow (e.g., magnitude, frequency, and timing; low-flows and high-flows),
- excludes metrics with large and significant differences between HSPF and stream gauge metric values from the highest priority set

Metrics in the first group can be evaluated with a high degree of confidence using either HSPF or stream gauge data in our set of streams. Metrics in the second group represent potentially important biological aspects of flow and can be evaluated with stream gauge data or with less confidence using HSPF data. These metrics could be used with greater confidence if HSPF models are calibrated specifically for these flow metrics.

Table 9. Hydrologic Metrics Selected for Testing against Biological Metrics.

Data Source	Priority for Testing	Flow Metrics	Rationale for Metric Selection and Data Source
GROUP 1 METRICS			
Either gauge or HSPF	High	Low Pulse Count High Pulse Count High Pulse Range Onset Fall Flows Fall Rate	• HSPF and stream gauge metrics are not significantly different (see Table 8), • HSPF calculated metrics can be used with high confidence; • Statistical redundancy is reduced; • Relationships with biology can be tested with flow data from both gauge and HSPF; • Biological importance of flow metrics expected to be high (see Table 5)
GROUP 2 METRICS			
Recommend gauge; HSPF data can be used with caveats	Medium	7-Day Minimum T_{QMEAN} % Time Above 2-yr Low Pulse Duration Low Pulse Range Daily Max:Mean Effective Stream Power Q2:Q10	• HSPF and gauge metrics are significantly different in this PSL data set, suggesting HSPF models may not simulate these metrics well (see Table 8), however, the difference between metric values may not be large (e.g., 7-day minimum flows, Table 8); • Flow metrics are expected to be important biologically (see Table 5); • Flow metrics capture aspects of flow not captured well in Group 1 metrics (e.g., geomorphically active flows; time between pulse disturbances)
GROUP 3 METRICS			
Recommend gauge data	Low	R-B Index Flow Reversals Rise Rate Fall Count Rise Count	• HSPF and gauge metrics are significantly different; • Redundant with flow metrics in Groups 1 and 2;

3.3 Relationships Between Hydrologic Alteration and Biological Metrics

3.3.1 Correlations Between B-IBI and Hydrologic Metrics

In our set of stream basins, B-IBI values are correlated with several of the flow metrics. However, the relationships between flow metrics and B-IBI are characterized by a great deal of scatter in biological values for a given hydrologic value (Figure 9). Correlation coefficients are similar for both HSPF and stream gauge metrics[16], although the correlation coefficients for the stream gauge metrics tend to be smaller than for the HSPF metrics. The stream flow data set from gauged sites had a smaller sample size (n = 11 POI's) than the modeled flow data set (n = 38 POI's).

For the stream gauge data metrics, significant correlations with B-IBI included the number of days between high and low pulse events, percent of time above the 2-year flow, and the date of the onset of fall flows (Figure 9). The B-IBI was not significantly correlated with T_{Qmean}.

For HSPF data metrics, B-IBI is correlated with the number of low and high pulse events, days between low and high pulse events, high pulse range, date of the onset of fall flows, normalized stream power, Q2:Q10, and T_{Qmean} (Figure 10). The B-IBI was not significantly correlated with the 7-day minimum flow (Figure 10). For HSPF data the clearest patterns in the bi-variate plots and strongest relationships suggested from bi-variate correlations are between the B-IBI and Q2:Q10, T_{Qmean}, effective normalized stream power, date of the onset of fall flows, low pulse counts, and days between high and low pulse events (Figure 10).

3.3.1.1 Correlations Between Biological Metrics and Hydrologic Metrics

In addition to correlations with B-IBI, a number of individual metrics were also significantly correlated with hydrologic metrics. With stream gauge flow metrics, the proportion of all individuals that are in the family Baetidae (Ephemeroptera) was positively correlated with an increasing number of low pulses, the total portion of the year with low pulses, and the portion of the year that daily flows are above the mean 2-year flow (Figure 11[17]). The proportion of all individuals that are Baetids was negatively correlated with T_{Qmean} and the number of days between low pulses (Figure 11).

[16] Figures 9 and 10, ** = correlations were significant at $p<0.001$; * = correlations significant at $p<0.01$

[17] In Figures 11-13, linear trend lines and linear R^2 are shown on the graphs.

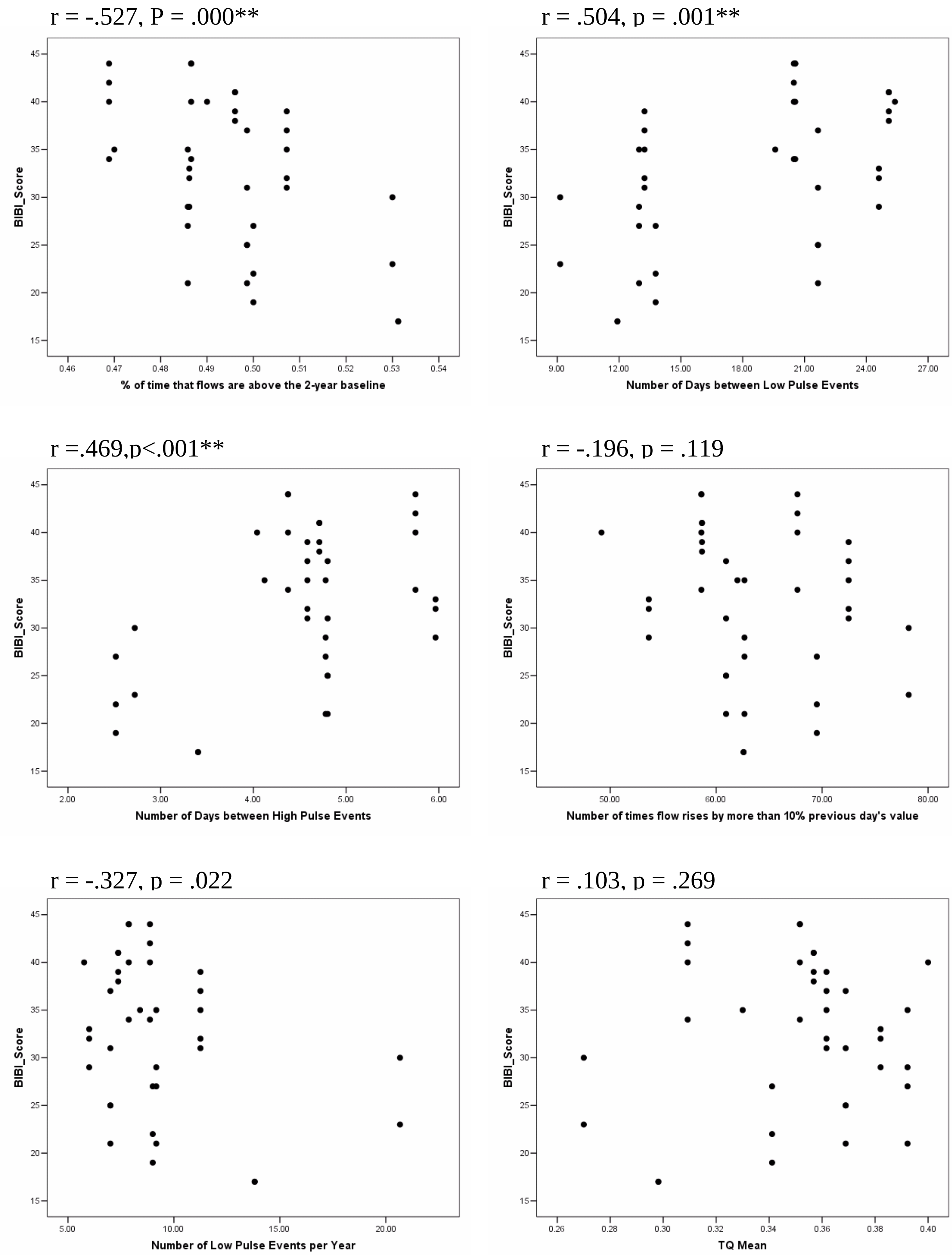


Figure 9. B-IBI for each site and year plotted against stream gauge metric values.

r=.450,p=.002**

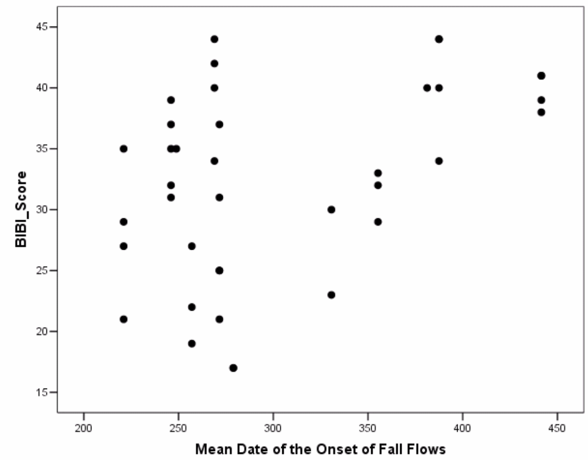


Figure 9. B-IBI for each site and year plotted against stream gauge metric values.

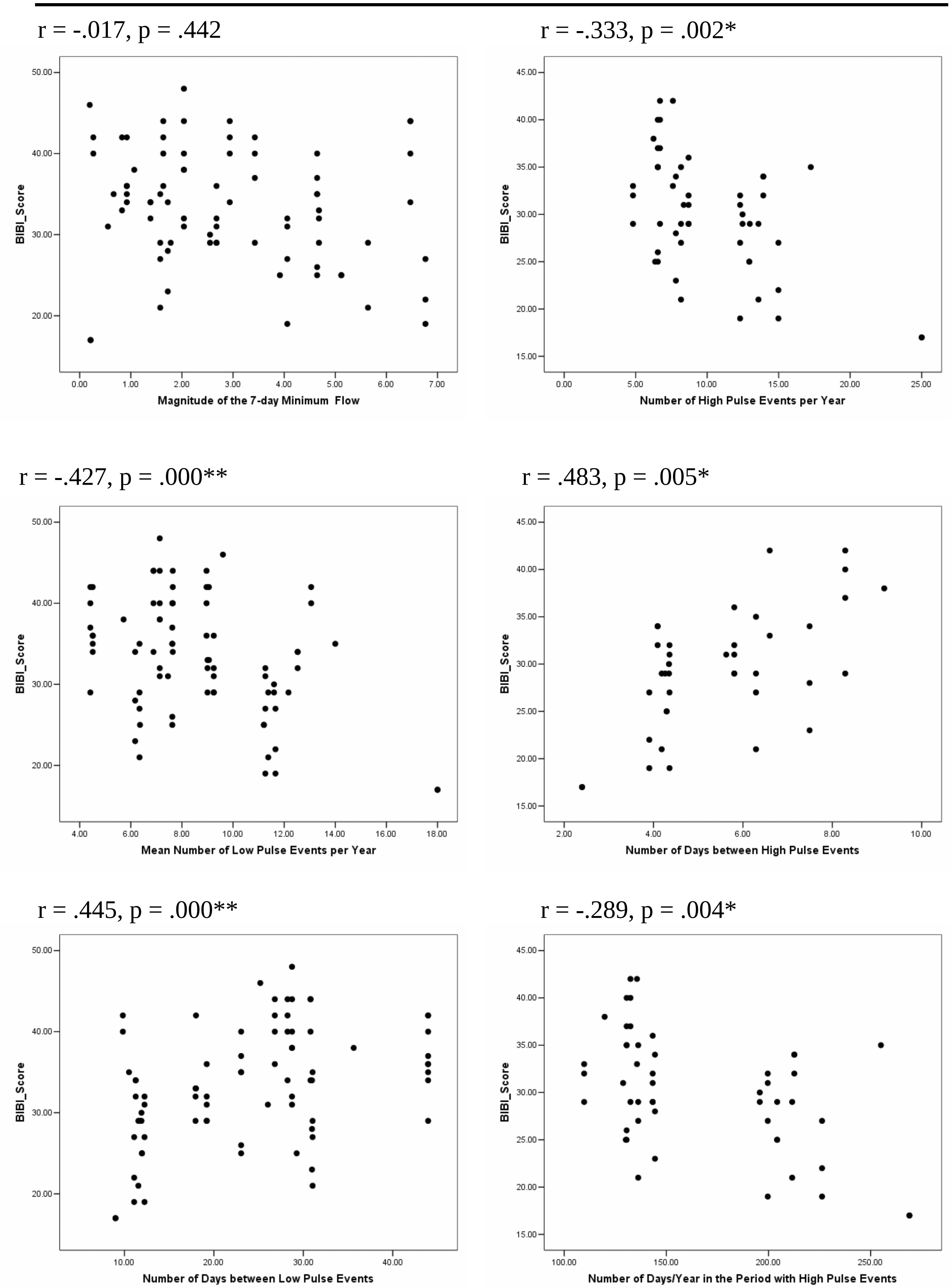


Figure 10. B-IBI for each site and year plotted against HSPF metric values.

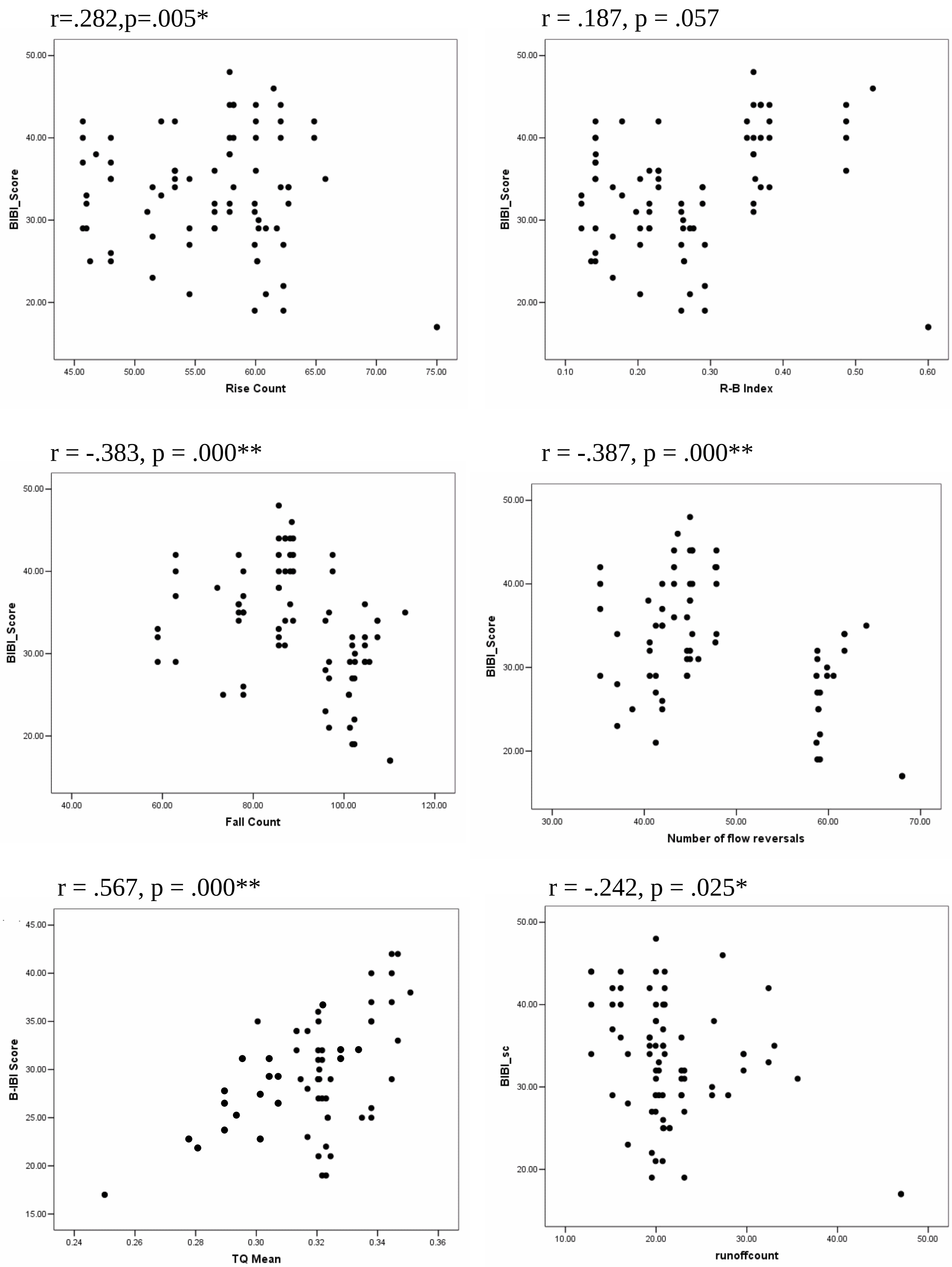


Figure 10. B-IBI for each site and year plotted against HSPF metric values.

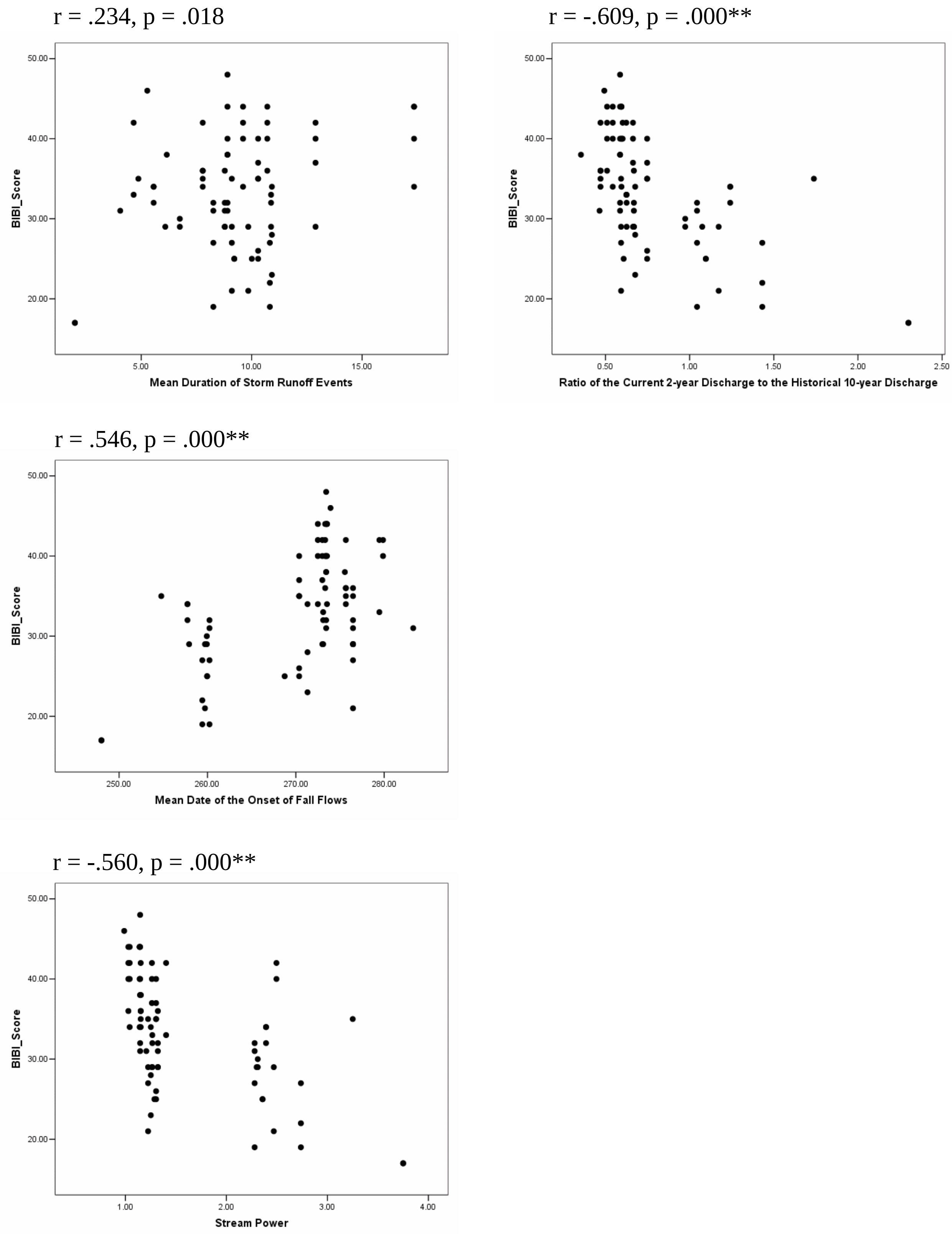


Figure 10. B-IBI for each site and year plotted against HSPF metric values.

The total number of taxa that have one or fewer generations per year (univoltine plus semivoltine taxa) is also correlated with several hydrologic metrics. The number of univoltine plus semivoltine taxa is positively correlated with T_{Qmean} and the date of the onset of fall flows, and negatively correlated with the number of high pulses per year, the portion of the year between the first and last high pulse events, and the portion of the year that daily flows are above the mean 2-year flow (Figure 12).

The total number of taxa that are clingers is positively correlated with values for the 1-day maximum flow of the year, T_{Qmean}, and the number of days between low pulse events (Figure 13). Clinger taxa number is negatively correlated with number of high and low pulse events, number of reversals, and portion of the year that flows are above the mean 2-year flow (Figure 13).

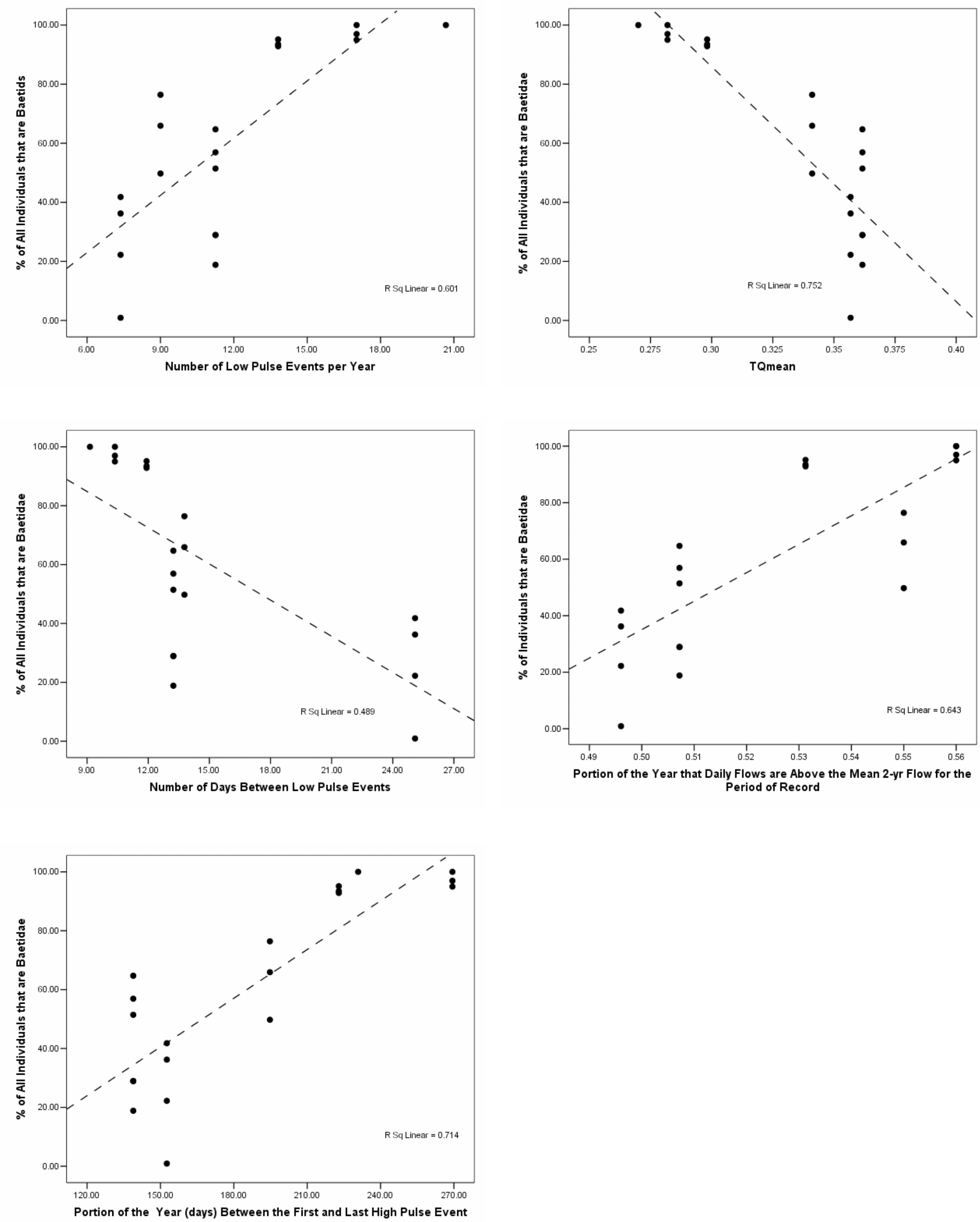


Figure 11. Proportion of Individuals that are in the Family Baetidae Plotted Against Stream Gauge Metric Values.

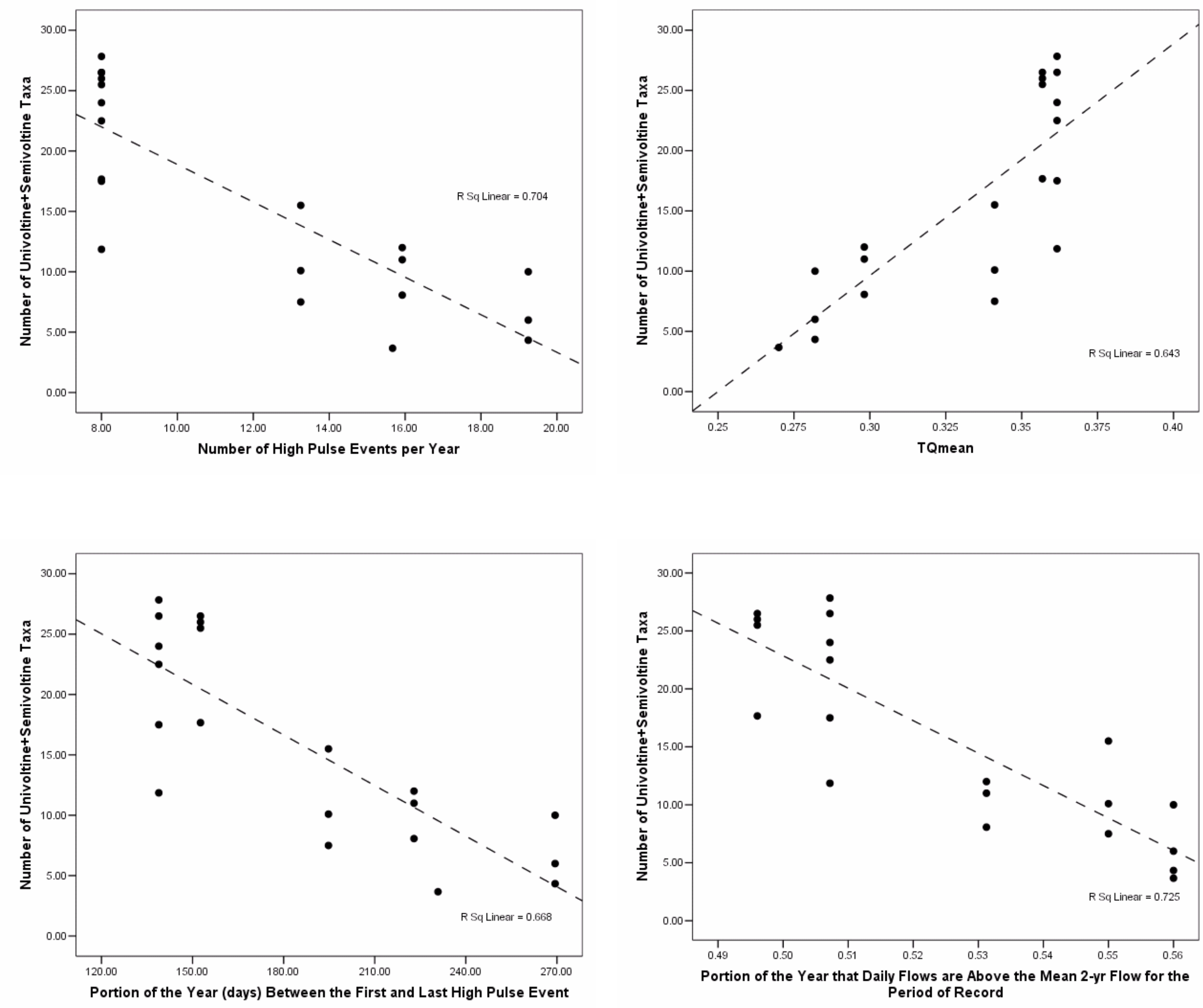


Figure 12. Number of Taxa with One or Fewer Generations per Year (univoltine + semivoltine) Plotted Against Stream Gauge Metric Values.

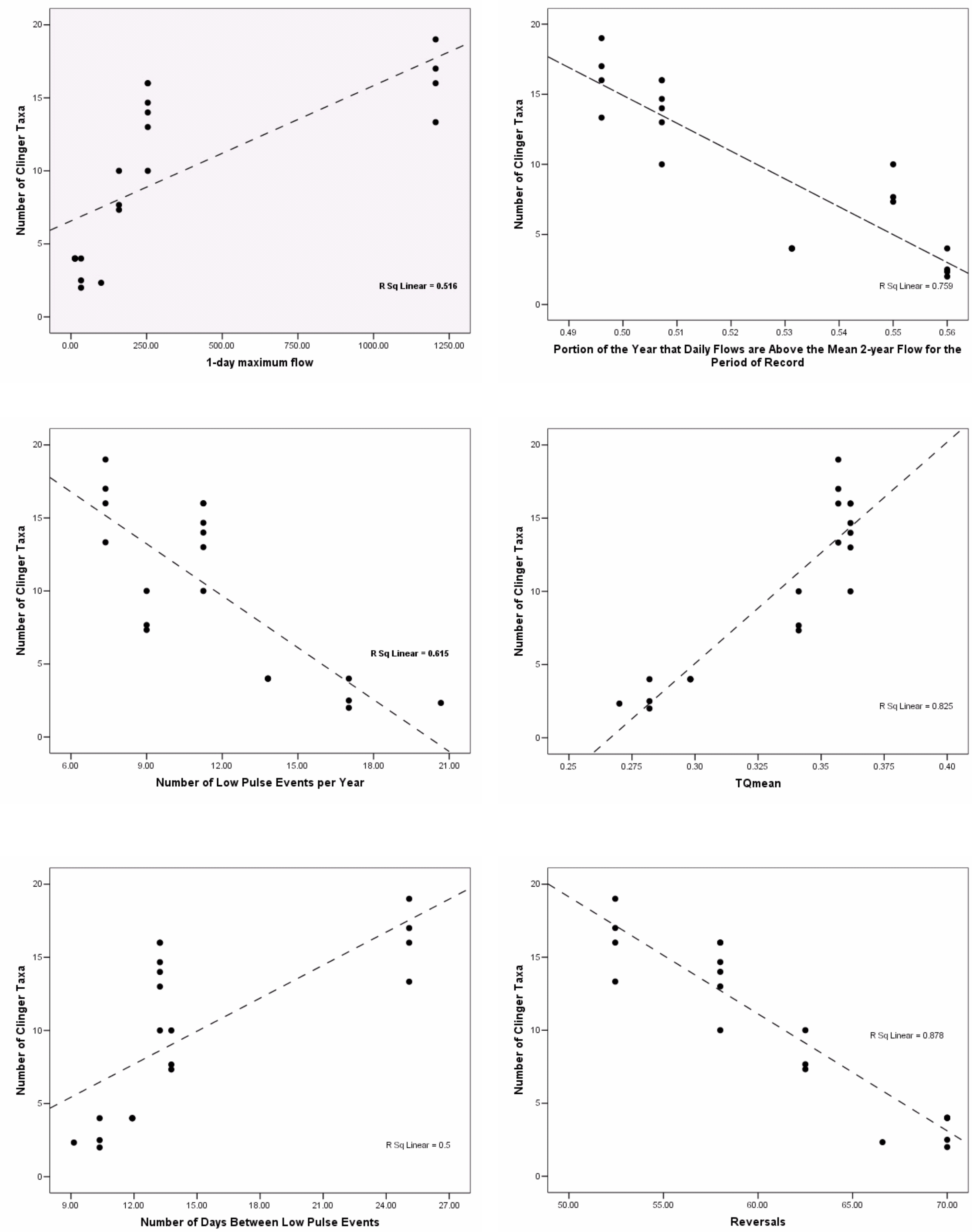


Figure 13. Number of Clinger Taxa Plotted Against Stream Gauge Metrics..

3.3.2 Influence of Local Riparian Condition

Local scale environmental factors may have a greater influence on benthic macroinvertebrates than sub-basin or basin-scale hydrology, or may mask the effects of these larger-scale factors. When the percent of individuals that are Baetids is plotted against the number of days between low pulse events, there is no clear relationship between the two metrics, although there is a lower bound to the cloud of points that trends down as the time between pulses increases (Figure 14A). Most of the sites plot in the upper left hand and lower right had corners of the graph (Figure 14A). These spaces correspond, respectively, to sites characterized by (1) a short period of time between pulse events during low-flows and communities dominated by Baetids (upper left hand); and (2) a longer period between pulse events during low-flows and communities not dominated by Baetids.

When the period between pulses is short (less than 10 days), all the sites are dominated by Baetids (Figure 14A). When the period between pulses is between 10 and 25 days, most of the sites are dominated by Baetids and all of these sites have more than 38% Baetids. When the period between pulses is greater than 25 days, most of the sites, but not all, have less than 50% Baetids. The community composition of sites characterized by more than 25 days between low pulses is variable, ranging from fewer than 10% to more than 90% of individuals as Baetids.

All of the sites in the upper right hand corner of Figure 14a, which have long periods between pulses and a high percentage of Baetids, are sites with less than 20% forest cover within 100m of the B-IBI sampling point (Figure 14b). Sites with a short period between pulses and dominated by Baetids do not exhibit a clear pattern in local forest cover; these sites range from almost no forest cover to over 90% forest cover within a 100 m radius (Figure 14b). There also does not appear to be a relationship between local forest cover and sites in the lower right hand corner of the graph, for those sites with longer periods between pulses and communities not dominated by Baetids. Local forest cover in these sites is also variable, ranging from 10% to 98%.

A similar pattern is evident when the percent of Baetids is plotted against the number of low pulse events and normalized effective stream power (Figure 15). All the sites with more than 10 low pulse events per year are dominated by Baetids (Figure 15a). Most of the sites with fewer than 10 pulse events per year are not dominated by Baetids. However, there are a number of sites that plot in the upper left hand of Figure 15a, these sites have a smaller number of low pulses and communities dominated by Baetids. Most of these sites also have less than 30% local forest cover. Similarly, when normalized effective stream power is greater than 1.5, all of the sites have more than 50% Baetids (Figure 15b). At normalized effective stream power greater than 1.5, there is a range of local forest cover values, with a few sites with more than 90% local forest cover and more than 90% individuals as Baetids. When normalized effective stream power is close to 1.0, community composition is highly variable. For these sites, the percent of individuals that are Baetids ranges from less than 10% to over 90%, with a correspondingly wide range of values for local forest cover (Figure 15b).

3.3.3 Timing of Fall Flows

The timing of fall flows is correlated with a number of biological metrics, including the B-IBI. For the number of taxa with longer generation times (i.e., one or fewer generations per year), timing of fall flows is positively correlated with the number of taxa; when onset of fall flows is earlier in the year there are fewer of these taxa (Figure 16). When the onset of flows occurs earlier in the year, around the 248th Julian day (beginning of August), there are no sites with high numbers of univoltine plus semivoltine taxa, even when these sites have more than 90% local forest cover (Figure 16). When the onset of fall flows occurs later in the year, the number of univoltine and semivoltine taxa is variable. Several of the sites with a late onset of fall flows and high numbers of univoltine plus semivoltine taxa have a low percent of local forest cover at the biological sampling site (i.e., < 20%), suggesting that late onset of fall flows may be more important than local riparian cover.

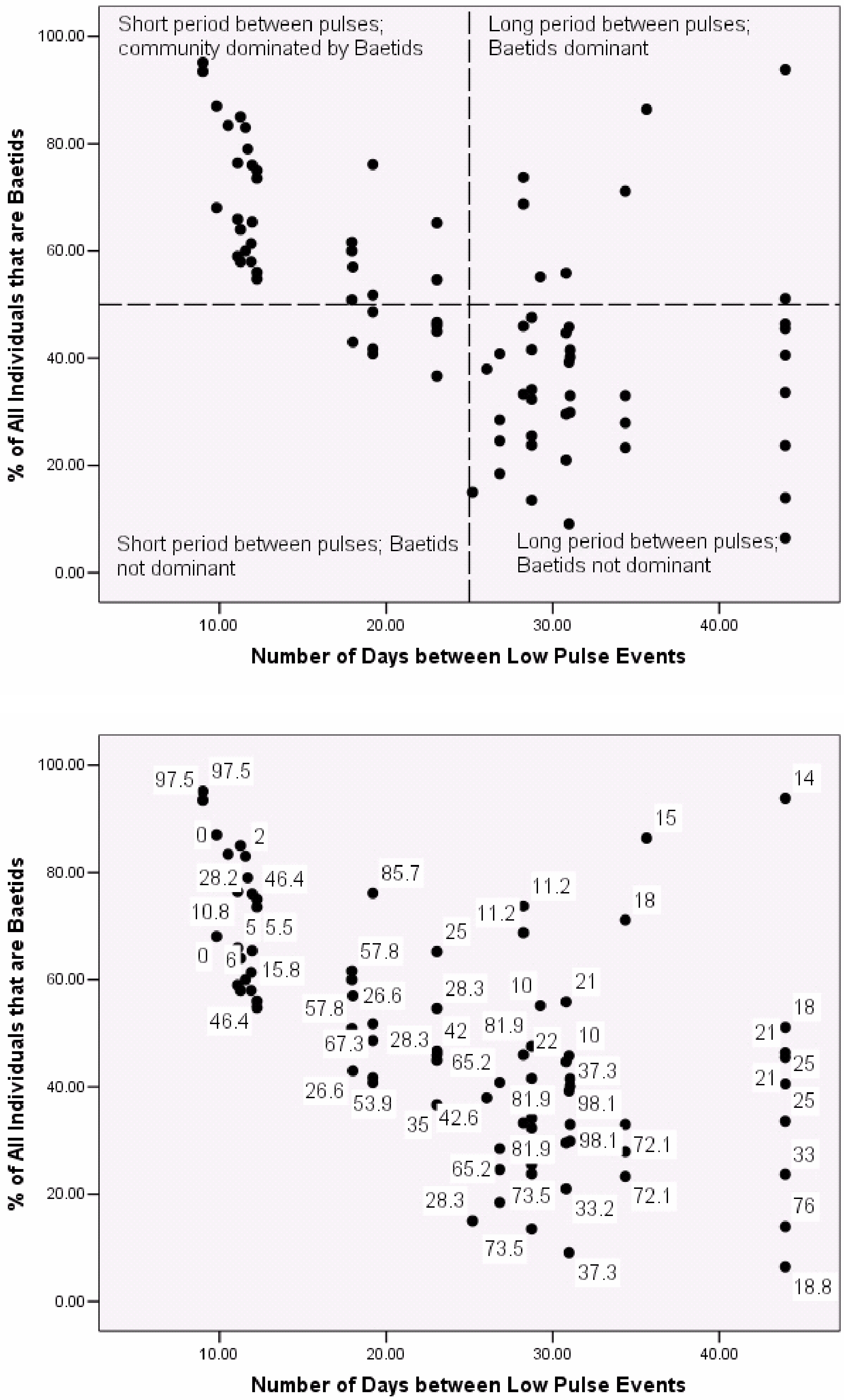
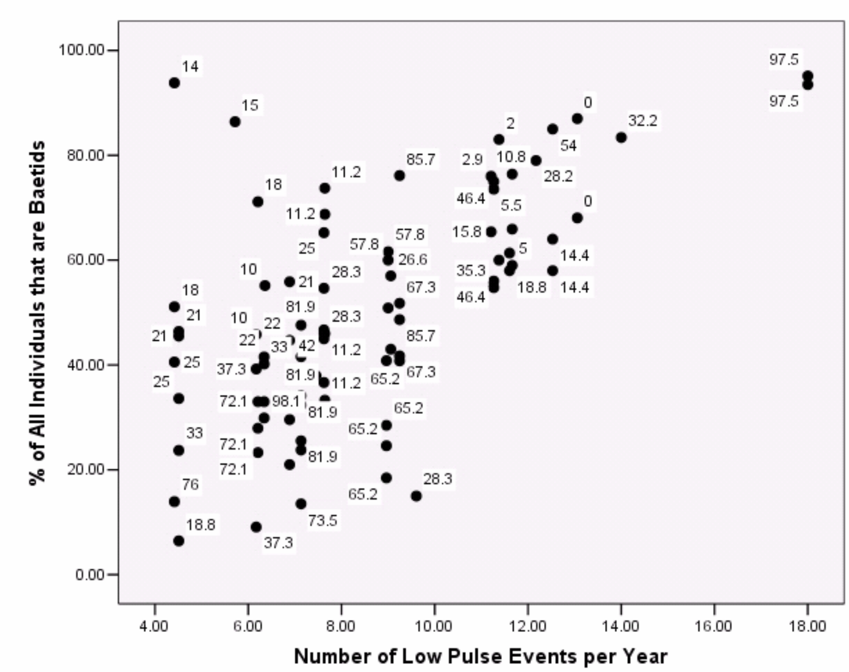


Figure 14. Proportion of Individuals that are Baetids plotted against Days Between Low Pulses (upper plot), with Percent Forest Cover in 100 m Radius of the B-IBI Site (lower plot).

a) % Baetids vs. Number of Low Pulses



b) % Baetids vs. normalized effective stream power

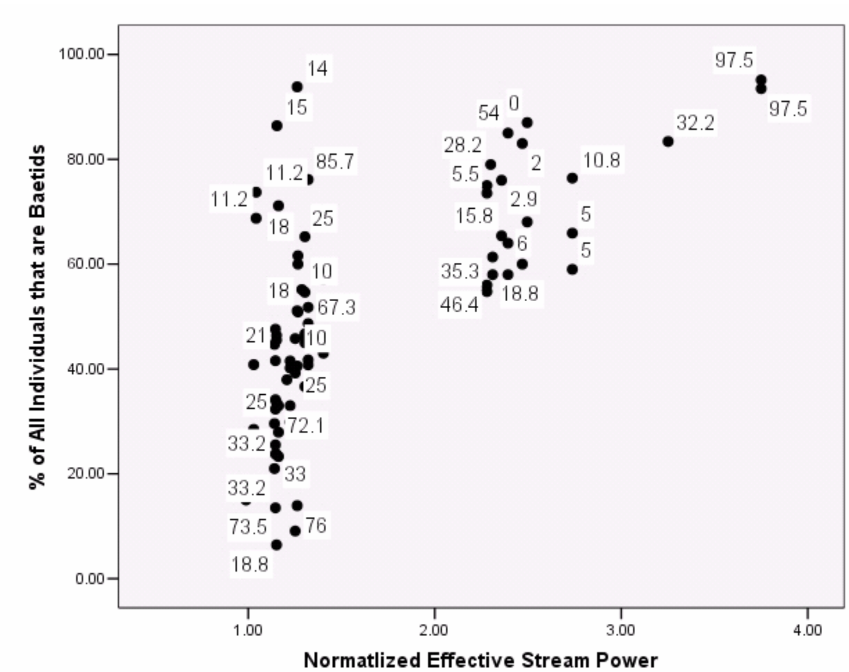


Figure 15. (a, b)Relationship Between Proportion of Individuals that are Baetids, Period Between Low Pulses, and Local Riparian Forest Cover.

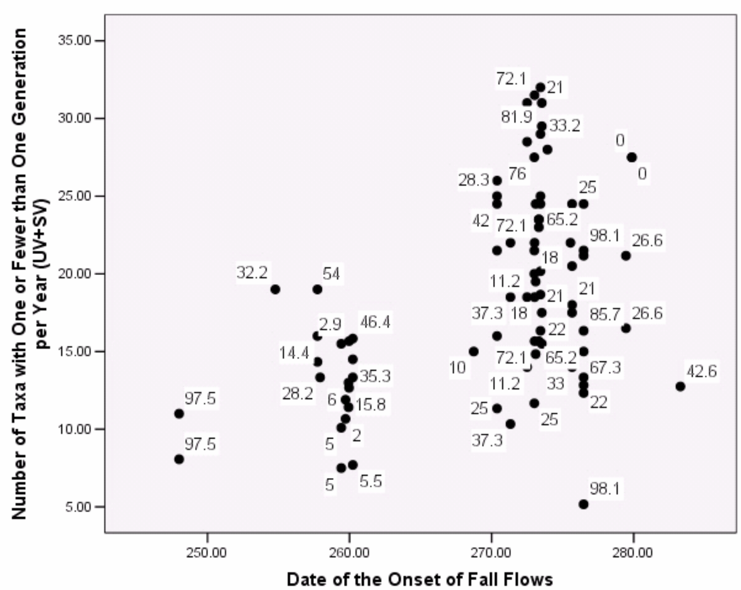


Figure 16. Taxa with One or Fewer Generations per Year Plotted against the Onset of Fall Flows; Percent Forest Cover within 100 m of the B-IBI site.

3.3.4 Differences in Hydrologic Metric Values Among B-IBI Groups

Sites classified based on biological condition differed in hydrologic metric values (gauge data) despite the variability in flow metric values within B-IBI groups (Figure 17). Biological groups were defined by B-IBI from Group 1 (worst sites based on B-IBI) to Group 4 (best sites based on B-IBI). Examination of Figure 17 suggests that B-IBI Group 1 has higher median values than Group 4 for high and low pulse events. B-IBI Group 1 also has lower median values for days between low pulses, earlier onset of fall flows, and smaller T_{Qmean}. The best and worst sites as classified by B-IBI were significantly different from each other, but 'fair' and 'good' sites were not always different (Figure 17).

We tested the null hypothesis that the four B-IBI groups have similar flow metric values, using the non-parametric Kruskal-Wallis test (Sokal and Rohlf 1984). Most of the flow metrics calculated from gauge data differed significantly among the B-IBI groups (Table 10A). For metrics calculated with stream gauge data, low and high pulse metrics, T_{Qmean}, the portion of time flows are above the mean 2-year flow, number of reversals, fall and rise rates, fall count, and the date of the onset of fall flows all differed between the best and worst groups (Table 10A). Rise count (gauge data) did not differ among the four B-IBI groups (Table 10A). Several flow metrics calculated with HSPF data also differed among the biological groups, including low pulse count, period between low pulses, high pulse count, period of the year with high pulses, effective stream power, onset of fall flows, ratio of the current 2-year to the forested 10-year flow, and fall rate (Table 10B).

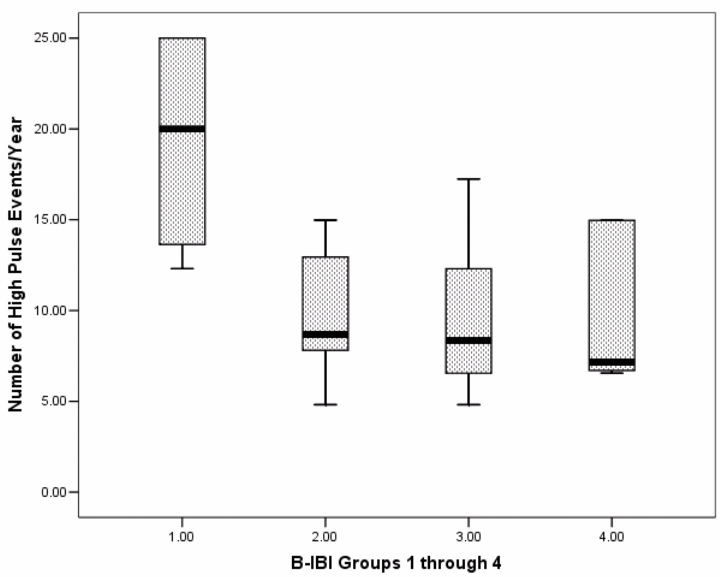
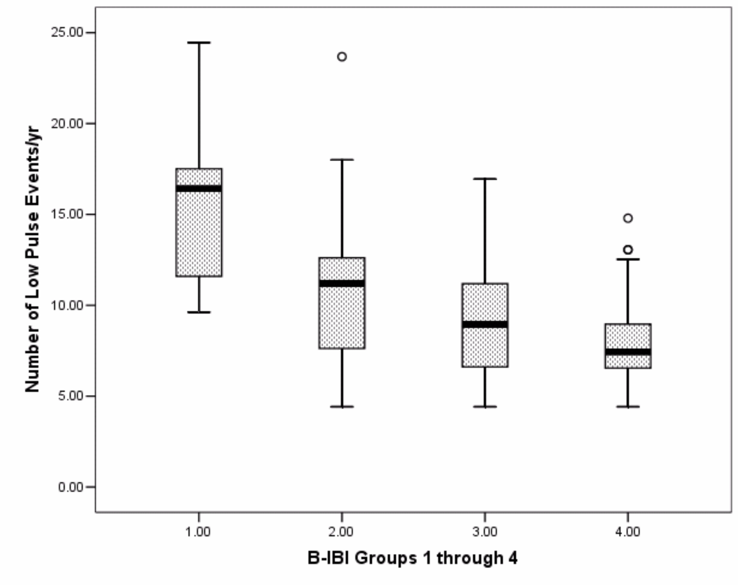


Figure 17. Median values of Stream Gauge Metrics for Four B-IBI Groups; (Group 1 – lowest B-IBI; Group 4 – highest B-IBI).



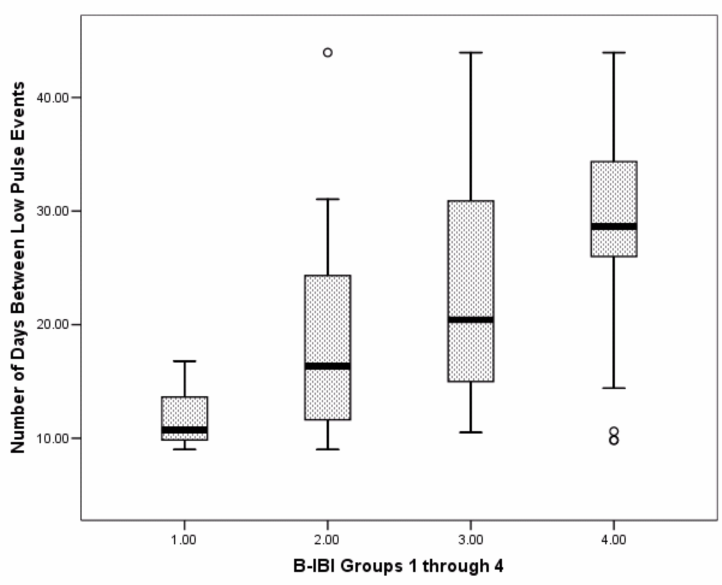
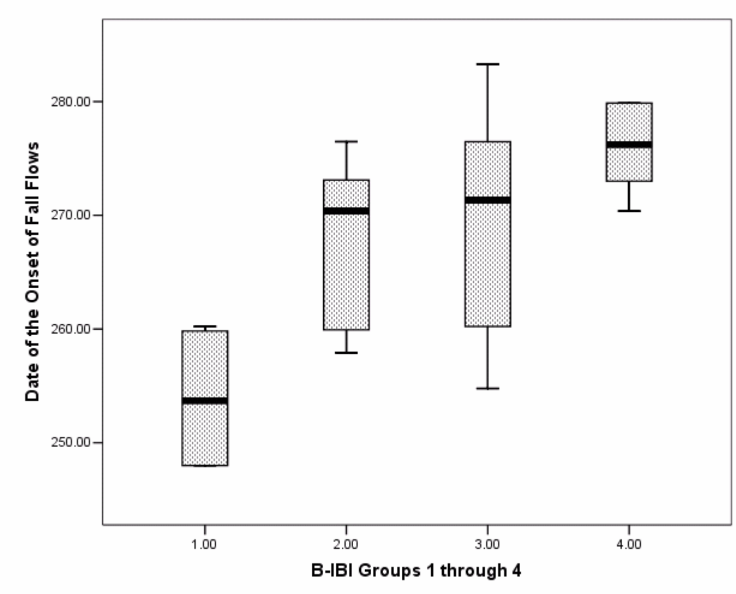


Figure 17. Median Values for Stream Gauge Metrics for Four B-IBI Groups; (Group 1 – lowest B-IBI; Group 4 – highest B-IBI).



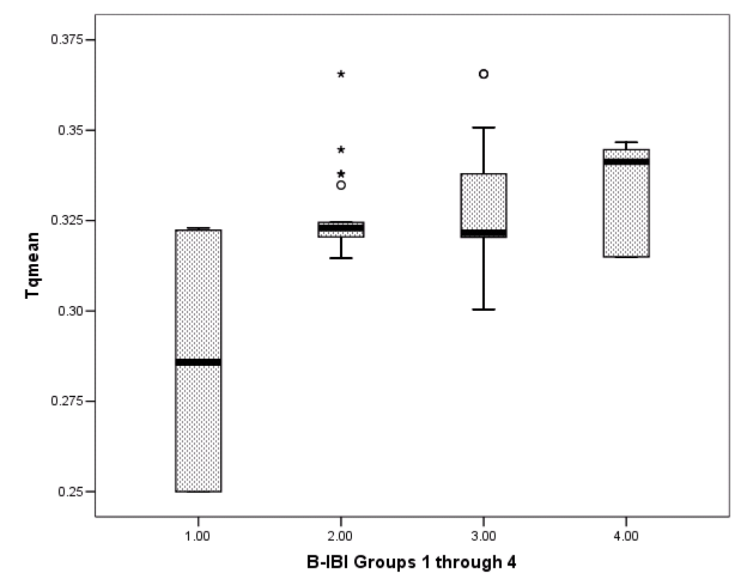


Figure 17. Median Values for Stream Gauge Metrics for Four B-IBI Groups; (Group 1 – lowest B-IBI; Group 4 – highest B-IBI).

Table 10. Flow metrics that differ between the four groups of sites defined by B-IBI score (Kruskal Wallis Test).

A. Hydrologic Metrics Calculated from Stream Gauge

	Chi-Square[18]	df[19]	p value.
7daymin	11.640	3	<0.01
1daymax	19.545	3	<0.001
Low Pulse Count	13.238	3	<0.01
Low Pulse Duration	15.625	3	<0.001
Low Pulse Range	9.517	3	<0.05
High Pulse Count	16.280	3	<0.001
High Pulse Duration	11.815	3	<0.01
High Pulse Range	18.153	3	<0.001
Fall Rate	12.780	3	<0.01
Rise Rate	15.171	3	<0.01
Fall Count	9.328	3	<0.10
Rise Count	6.795	3	NS
Tqmean	14.423	3	<0.01
%above2yr	18.480	3	<0.001
OnsetFall	22.468	3	<0.001
Reversals	17.855	3	<0.001

B. Hydrologic Metrics Calculated from HSPF Flow Data

	Chi-Square	df	p value
7daymin	5.959	3	NS
Low Pulse Count	6.501	3	<0.10
Low Pulse Duration	6.756	3	<0.10
High Pulse Count	7.582	3	<0.10
High Pulse Range	8.690	3	<0.05
%above2yr	5.425	3	NS
Eff. Stream Power	7.386	3	<0.10
Q2_Q10	11.166	3	<0.05
Onsetfall	11.365	3	<0.010
Low Pulse Range	3.562	3	NS
Fall Rate	15.922	3	<0.001
Tqmean	3.437	3	NS

a Kruskal Wallis Test
b Grouping Variable: BIBI Group

[18] Test statistic; must be greater than 6.0 to be significant at $\alpha<0.10$

[19] Degrees of freedom with four biological groups

4.0 DISCUSSION AND CONCLUSIONS

4.1 Use of HSPF Flow Data for Evaluating Flow Alteration

There are advantages to using both types of flow data in evaluating hydrologic alteration and linkages to biological effects in PSL streams. Use of simulation models would allow managers to predict future hydrologic conditions under different development and land cover scenarios. Simulation models can also be used to estimate the degree of hydrologic alteration between pre-, current, and future development scenarios. Metrics of departure of degree of alteration are normalized and can be used to compare hydrologic alteration in systems that may differ naturally, for example, in degree of flashiness. One advantage of stream gauge flow metrics is that they are more reflective of the actual change in the flow conditions that stream biota experience, because these metrics integrate the effects of changing land use over the period of record.

The major disadvantage of HSPF simulation models is that they are generally not calibrated for the types of flow metrics investigated in this study (e.g., low-flows, small pulse events, timing of events). Therefore, the use of HSPF data for evaluating flow alteration and biological response will need to incorporate an understanding of the error associated with the models used in specific stream basins in terms of the flow metrics of interest. Use of existing simulation models should incorporate re-calibration specifically to capture ecologically relevant flow alterations. Finally, analysis of ecologically relevant flow attributes may require the development of new HSPF or other simulation models conceptually derived from ecological models of river and stream ecosystems.

4.1.1 Implications for the Use of Both Types of Flow Metrics

This study demonstrates that both HSPF and stream gauge flow data are useful in deriving hydrologic metrics related to increasing urbanization, and indicative of the type and extent of hydrologic alteration in urban PSL streams. Both types of flow data showed similar patterns with increasing percent EIA, suggesting that both types of data capture general hydrological responses related to changing land use patterns. Both types of data also showed similar patterns in relationship to the biological metrics and both have potential utility in relating flow changes to biological conditions in PSL streams. However, there were significant differences in the metric values depending on data source, indicating that use of HSPF data without careful calibration could result in spurious relationships between flow and biology, or in an inaccurate characterization of the flow changes that have occurred with urbanization.

We did expect however, that metric values would differ somewhat between the two data sources. We used HSPF flow data under a single land cover value, from 1995, as a measure of current levels of urbanization. In contrast, the stream gauge flow data reflects a range of land cover values that were changing over the period of record, which spans the years prior to, and after, 1995. Because urbanization is on-going in many of these basins, and most basins were more urbanized in 2002 than they were in 1995, observed stream flow data reflects these on-going land cover changes while the HSPF simulations do not. In stream basins where urbanization has occurred more recently, changes in runoff and flow patterns, as well as biological responses, may still be occurring in response to these more recent changes. These more dynamic responses to recent land use changes would be reflected in the stream gauge data but not in the HSPF flow data. Finally, stream gauge metrics were based on a smaller sample size and a shorter period of record, both of which would tend to increase variability compared to the HSPF metrics.

One advantage of using HSPF models is that a better spatial and temporal match can be achieved between flow and biological sampling stations or data collection points. Stream gauge locations are typically limited to a few places within a particular stream basin, typically at the mouth or just above tributary confluences, in order to capture moderately-sized basin hydrology. The period of record for many stream gauges in the PSL is also limited to short (< 15 years) and recent time periods. This limits the extent to which biological and flow data can be matched to the spatial and temporal patterns of flow. Better spatial and temporal matching would enhance our ability to determine the relative importance of variation in flow on biological conditions.

4.1.2 Use of HSPF Flow Metrics for Evaluating Flow Alteration and Biological Condition

4.1.2.1 Recommended Metrics

The comparison of metric values from stream gauge and HSPF sources suggests that some of the metrics that we chose because of their expected biological significance are not well estimated by HSPF models. Most of the metrics were significantly different when calculated from the two data sources. However, a small number of the metrics were not different between HSPF and stream gauge data. These metrics can be used with HSPF models, using standard calibrations, to evaluate flow alteration in PSL streams:

- Low pulse count
- High pulse count
- High pulse range
- Fall rate
- % of time above the mean 2-year flow
- Date of onset of fall flows
- T_{Qmean}

Metrics in this group can be evaluated with either existing HSPF models or stream gauge data in our set of PSL streams. This group alone captures a suite of useful metrics that also reduces redundancy among the flow metrics. Metrics with clear differences in metric values depending on data source (Table 8), represent potentially important biological aspects of flow and can be evaluated with stream gauge data or with HSPF data if models can be calibrated specifically for these metrics.

4.1.2.2 Calibrating HSPF Models for Use with Hydrologic Metrics

Our results suggest the importance of calibrating HSPF, or other flow simulation models, specifically for the flow metrics of interest for ecological studies or for management applications. HSPF models are most typically calibrated for use with stormwater management policies and facility design. The flow metrics that are important for stormwater management applications are typically very different from the types of flow metrics discussed here. In particular, metrics that describe aspects of flow timing or that attempt to capture biologically relevant thresholds for pulse events, should be included in HSPF calibrations if these models will be applied in a stream ecosystem management or restoration context.

4.2 Relationships between Flow and Biological Condition

4.2.1 B-IBI and Flow Metrics

Relationships of B-IBI with hydrologic metrics such as T_{Qmean} and Q2:Q10 are consistent with those found in previous studies in the PSL (May et al. 1997, Morley and Karr 2002, Booth et al. 2004). In our analysis, sites with higher B-IBI could be discriminated from sites with low B-IBI by a new set of hydrologic variables that may reflect the relative level of hydrologic disturbance for these streams. Higher B-IBI were characteristic of sites with a longer period of more stable flows between pulses above high- or low-flow thresholds, fewer of these pulses per year, a shorter portion of the year with high pulses, later onset of fall flows, and a less flashy hydrograph (e.g. number of reversals, fall rates). The better biological sites based on B-IBI groups also were streams with fewer or shorter duration flow events that may physically alter channels or move bed sediments, such as fewer days that flows are above the mean 2-year flow, and lower effective stream power.

Benthic macroinvertebrates could be more influenced by particular antecedent flow events than by average flow values over a period of years. For example, an extreme summer drought just prior to B-IBI sampling, may have a strong short-term effect that masks the longer-term effects of lower flows on average during the summer months. Because of the lack of long term paired biological and flow data sets for our streams we could not adequately evaluate this possibility. The effects and relative importance of antecedent flow events should be evaluated if longer-term biological and hydrologic data sets are available.

The timing of flow events is thought to be important biologically; however, very few timing metrics have been developed or tested with biological data. In our streams, the onset of fall flows captures the increase in small peaks and pulses that occur during the late summer and early fall months in urban streams, but not in streams in forested basins. The onset of fall flows was correlated with general biological condition (B-IBI), as well as a number of the individual metrics. Our definition of this metric however, is the timing of the first increase in flows following the lowest 1-week low-flow period. As such, the first onset of fall flows could be a large flow event or a small flow event.

Both large and small pulses following a prolonged period of stable low-flows could be important biologically, as cues for behavioral responses such as migration, as flushing flows that mobilize nutrients or organic materials, or physical disturbances associated with larger events. Because the changed timing could have a number of biological effects depending on the nature of the first fall flow increase, additional metrics should be developed that capture the timing of fall flows at different thresholds. For example, metrics that distinguish between the increase in small pulses during late summer and fall, as well as the timing of the first prolonged higher flow events that can reconnect side channels or trigger migrations.

The macroinvertebrate data sets used in this analysis represent the most comprehensive and extensive biological data set for PSL streams. The B-IBI incorporates diagnostic information within the ten metrics that allows interpretation of the causal mechanisms responsible for differences in B-IBI among sites (Karr and Chu 1999). For example, the sediment intolerant taxa and tolerant taxa metrics provide information about the importance of water quality impairment relative to other factors. However, because it was not designed to test for effects of flow alteration, but integrates the effects of many stressors, including but not limited to flow, the power of this B-IBI data set to evaluate the relative importance of flow as a stress may be limited. Interestingly, however, the B-IBI data set may be relatively sensitive to the late summer/early fall timing metrics, such as the onset of fall flows. Because B-IBI data are collected in late August to mid- to late-September, the taxa present at these sites in September may reflect short-term responses to late summer/early fall flows and/or longer-term responses to a shift in the timing of the beginning of fall flows.

4.2.2 Individual Diagnostic Biological Metrics

Several of the individual biological metrics we tested have the potential to provide diagnostic information about flow conditions. The percent of Baetid individuals, Clinger taxa, and the number of taxa that are univoltine plus semivoltine can provide diagnostic information about particular flow stresses that may be important and present in a given system. Benthic macroinvertebrate taxa that are expected to tolerate flow disturbances (resistant), or recover better from disturbances (resilient), may be sensitive indicators of the type and degree of flow alteration in PSL streams. For example, taxa that are smaller and have shorter reproductive cycles (e.g., Baetids), would be expected to recover more quickly from flow disturbances than taxa that have longer reproductive cycles and lower population growth rates (e.g., univoltine plus semivoltine taxa).

Ephemeroptera in the genus *Baetis* tend to be highly mobile, have short life spans and many are multi-voltine – all traits which could allow these taxa to avoid disturbance or recolonize and recruit rapidly following disturbance (Peckarsky et al. 2000). These taxa were more abundant when stream power was higher, Q2:Q10 was larger, low pulse events were closer together, when there were more high and low pulse events, and when there was a longer period of time in the year disturbed by high or low pulse events. The correlation of Baetid abundance with these flow measures suggests that Baetid taxa recover more quickly following flow disturbances than other taxa in PSL streams and may be sensitive indicators of flow disturbance.

The relative importance of non-flow factors must also be included in interpreting the relationship between flow and Baetid abundance (or other biological metrics). For example, because many Baetids are herbivores, Baetid abundance is related to the amount of light reaching the stream and thus, to algal abundance. The interplay of flow disturbances and algal abundance may explain much of the variation in Baetid abundance in PSL streams.

Clinger taxa were expected to tolerate greater flow velocities and higher flows than other taxa and to be more resistant to flow disturbances. Clinger taxa richness is positively correlated with B-IBI, which is negatively correlated with measures of flow disturbance in our data set. However, when tested against hydrologic metrics, clinger taxa richness is positively correlated with one hydrologic metric related to high flows. Clinger taxa were more abundant as the magnitude of the 1-day maximum flow increased, but were less abundant as the number of high pulse events and low-flow pulse events increased. This suggests that individual high flow events may be tolerated well by clingers, while an increase in the frequency of high pulses, or in pulse events that occur during normally low, stable flow periods are not well tolerated. Similarly, clinger taxa abundance was higher when the number of days between low pulse events was greater (i.e., fewer clingers when recovery time between events was short), suggesting that frequent pulse events with short recovery times during low-flow periods may have a negative impact on clinger taxa.

Univoltine plus semivoltine taxa were not expected to recover as rapidly from flow disturbances as other taxa and these taxa were negatively correlated with several measures of flow disturbance such as the number of high and low pulse events, time above the mean 2-year flow, portion of the year with high or low pulses and the onset of fall flows.

We expected that the timing of hydrologic events would be important to benthic macroinvertebrates; however we were limited by a lack of information on the timing of specific events that should be important to benthic macroinvertebrates in PSL streams. Interestingly however, the timing of the onset of fall flows was related to B-IBI and was a discriminating variable explaining variation among groups of sites based on B-IBI. In addition, the number of taxa with one or fewer generations per year was positively correlated with the onset of fall flows – the later fall flows begin, the greater the number of these taxa. Because of their potential importance biologically, additional seasonal or timing hydrologic metrics should be investigated. Seasonal or timing flow metrics that are tied to specific life history stages of dominant taxa, for example periods of oviposition or emergence of aquatic insects, could potentially be useful predictors of the biological consequences of specific flow alterations.

4.2.3 Relative Effects of Local Site Conditions and Sub-basin Hydrology

The patterns of biology-hydrology relationships in our scatter plots are typical of ecological responses to multiple limiting factors (see Figure 10) (Cade et al. 1999, Huston 2002). This pattern of scatter shows an upper (or lower) bound or edge to the cloud of points, with much scatter below or above this bound (Cade et al. 1999). Such a 'factor ceiling' distribution implies that the upper bound of the cloud of points is defined by the predictive or limiting variable (i.e., hydrologic metric) and other environmental factors explain the scatter beneath this ceiling. Similar relationships have been found with B-IBI plotted against total impervious area (Karr 1998, Morley and Karr 2002). In our plots, some of the scatter can be explained by the combination of local forest cover and flow metrics. This suggests that when local habitat conditions are not limiting (i.e. relatively intact forested riparian zone), sub-basin scale hydrologic conditions are important in influencing local biological condition. In contrast, for some metrics (uni-voltine plus semi-voltine and onset of fall flows), the effects of flow predominated such that high quality local riparian conditions did not offset the effects of early fall flows.

Hydrology would not be expected to completely explain variation in biological metrics because other factors likely to be important, such as water quality, are not captured by the measure of local riparian condition that we used. However, a significant amount of pattern in the biological metrics is explained by hydrologic variables, and the amount of variation in biology that is explained by hydrology increases when one non-flow factor is included. Additional non-flow environmental factors should be included in future analyses to further explore the relative importance of flow versus other factors on benthic macroinvertebrates. Based on these results, non-flow factors related to how changes in flow disturbance regimes translate into biological effects may be particularly important. For example, channel morphology in terms of refugia from high or low-flows, or substrate size and type will affect whether increases in frequency or duration of high pulses result in biologically trivial or significant impacts on stream organisms.

4.2.4 Relevance of Flow and Biological Metrics for Management

This study demonstrates that a small number of flow metrics may be used to capture biologically relevant aspects of flow alteration in PSL streams. With further work to verify the relationships, the combination of flow and biological indicators suggested here could be used explicitly to inform management applications such as the evaluation of stream ecosystem conditions and development of restoration plans or stream management programs. The flow metrics developed here respond consistently to increasing levels of urbanization and are related to changes in biological condition. Biological measures that reflect both general condition (B-IBI) as well as individual metrics that contain more diagnostic information about the relative influence of flow and other environmental factors can be related to changes in flow metrics in PSL streams. With our limited data set, the 'best' and 'worst' sites biologically (based on B-IBI or individual metrics) can be distinguished using hydrologic metrics.

The flow metrics with the best correlations with biology include those that indicate a change in disturbance regime (intensity, duration, or frequency of disturbance) or a change in the timing of flow events. This set captures various aspects of the flow regime (magnitude, frequency, duration, timing, rate of change), minimizes redundancy among flow metrics, and has strong correlations with biological metrics:

- Low-flow threshold pulse events and interval between pulses
- High-flow threshold pulse events and total period of the year with high pulses
- T_{Qmean}
- Percent of time above the mean 2-year flow
- Timing of the onset of fall flows

Our ability to evaluate and manage flow alterations in PSL streams would also benefit from the development of additional biological metrics that may respond to flow changes differently than benthic macroinvertebrates, for example metrics that represent larger spatial scales and longer temporal scales. Developing and testing metrics for other taxonomic groups, such as fish or algae, would enhance our ability to interpret the biological effects of flow changes, as well as to manage stream systems for a range of biological taxa of interest. Such a variety of metrics would more accurately represent ecosystem attributes and provide a more comprehensive context for management.

HSPF or other simulation models have utility in evaluating hydrologic change and relating these changes to biological condition, as well as for simulating future development and/or restoration scenarios for managers. However, simulation models should be used with caution until they can be specifically calibrated for flow metrics of biological interest. In addition, many additional factors influencing historical or natural flow regimes (i.e., influence of large wood, beavers, historical wetland extent) as well as factors influencing current and future flow (i.e., influence of groundwater withdrawals on summer baseflows) may not be included in current HSPF models, or may not be accurately estimated by these models.

One limitation of this study was the lack of hydrologic and biological data, and in particular, data explicitly developed to test predictions about relationships between anthropogenic change, flow alteration, and biological response. Evaluation and management of stream ecosystems in the PSL would benefit from the availability flow, habitat, and biological data sets that are designed to address system response to flow alteration.

4.3 Index of Hydrologic Integrity - IHI

Managers responsible for protecting or restoring aquatic ecosystems are currently faced with a large number of hydrologic metrics that can be used to evaluate flow regimes and the departure from natural flow conditions (Richter et al. 1996, Olden and Poff 2003). Attempting to derive and apply information from so large number of flow metrics may not be practical in many management contexts, and guidance for selecting a smaller, more easily applied set of metrics is limited (see Olden and Poff 2003). In particular, there has been little guidance for readily identifying the biologically meaningful flow metrics from among the many potential metrics available to managers. Development of a simple index of hydrologic integrity (IHI), which indicates departure from natural flow conditions and is biologically meaningful, would be very useful.

An index that combines the metrics tested here, which capture major attributes of the flow regime, are related to biological attributes, and change with increasing urbanization, could be a powerful tool for managing flows and restoring watersheds to improve stream biological conditions. An IHI could be used to assess the relative condition of flow regimes in stream systems, and suggest which components of the flow regime should be the focus of management and restoration efforts. Such an index could readily be used to evaluate the relative hydrologic integrity of sub-basins within watersheds to support watershed restoration priorities and decisions about where hydrologic integrity can best be protected, managed and/or restored. An IHI could be used to evaluate the effectiveness of proposed habitat restoration actions in terms of the sustainability of reach-scale or site specific habitat restoration in the context of current levels of hydrologic alteration within a sub-basin or watershed. Constructing such an index from metrics describing biologically relevant aspects of the flow regime for PSL streams could provide managers with an easy to use and meaningful tool for assessing stream condition, in combination with other commonly used tools, such as the B-IBI.

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Appendix A

Appendix A-1. Correlations among Hydrological Metrics – Stream Gauge Data

Metric		7-Day Minimum Flow	1-Day Maximum Flow	Date Minimum Flow	Date Maximum Flow	Low Pulse. Count	Low Pulse Duration	Low Pulse. Range	High Pulse. Count	High Pulse Duration	High Pulse Range	Fall Rate	Rise Rate	Fall. Count	Rise. Count	Tqmean	R-B Index	Daily Max: Daily Mean Flow	%above2yr	OnsetFall	Reversals
7daymin	Pearson Correlation	1	.925(**)	.102	.033	-.573(**)	.689(**)	-.488(**)	-.403(**)	.185	-.381(**)	-.941(**)	.921(**)	-.512(**)	-.489(**)	.485(**)	-.475(**)	-.275	-.069	.182	-.377(*)
	Sig. (2-tailed)		.000	.504	.829	.000	.000	.001	.006	.224	.010	.000	.000	.000	.001	.001	.001	.067	.654	.232	.011
	N	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45
1daymax	Pearson Correlation	.925(**)	1	.166	.220	-.483(**)	.717(**)	-.224	-.358(*)	.245	-.253	-.995(**)	.993(**)	-.366(*)	-.413(**)	.289	-.349(*)	.000	-.210	.350(*)	-.331(*)
	Sig. (2-tailed)	.000		.277	.147	.001	.000	.139	.016	.105	.093	.000	.000	.014	.005	.055	.019	.999	.165	.018	.026
	N	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45
mindate	Pearson Correlation	.102	.166	1	.386(**)	-.183	.282	-.061	-.141	.026	-.006	-.162	.174	-.227	-.230	.010	-.018	.256	-.324(*)	.365(*)	-.130
	Sig. (2-tailed)	.504	.277		.009	.229	.061	.690	.354	.865	.968	.288	.253	.134	.128	.950	.906	.090	.030	.014	.393
	N	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45
maxdate	Pearson Correlation	.033	.220	.386(**)	1	.012	.477(**)	.582(**)	.085	.285	.253	-.164	.202	-.137	-.342(*)	-.393(**)	.220	.645(**)	-.150	.254	-.135
	Sig. (2-tailed)	.829	.147	.009		.938	.001	.000	.577	.058	.094	.282	.184	.369	.022	.008	.147	.000	.324	.092	.376
	N	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45
Low Pulse Count	Pearson Correlation	-.573(**)	-.483(**)	-.183	.012	1	-.812(**)	.651(**)	.808(**)	-.657(**)	.756(**)	.477(**)	-.455(**)	.762(**)	.740(**)	-.791(**)	.892(**)	.583(**)	.339(*)	-.411(**)	.818(**)
	Sig. (2-tailed)	.000	.001	.229	.938		.000	.000	.000	.000	.000	.001	.002	.000	.000	.000	.000	.000	.023	.005	.000
	N	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45
Low Pulse Duration	Pearson Correlation	.689(**)	.717(**)	.282	.477(**)	-.812(**)	1	-.285	-.622(**)	.647(**)	-.485(**)	-.693(**)	.693(**)	-.724(**)	-.762(**)	.463(**)	-.623(**)	-.172	-.286	.435(**)	-.763(**)
	Sig. (2-tailed)	.000	.000	.061	.001	.000		.058	.000	.000	.001	.000	.000	.000	.000	.001	.000	.259	.057	.003	.000
	N	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45

Metric		7-Day Minimum Flow	1-Day Maximum Flow	Date Minimum Flow	Date Maximum Flow	Low Pulse. Count	Low Pulse Duration	Low Pulse. Range	High Pulse. Count	High Pulse Duration	High Pulse Range	Fall Rate	Rise Rate	Fall. Count	Rise. Count	Tqmean	R-B Index	Daily Max: Daily Mean Flow	%above2yr	OnsetFall	Reversals
Low Pulse Range	Pearson Correlation	-.488(**)	-.224	-.061	.582(**)	.651(**)	-.285	1	.558(**)	-.153	.669(**)	.266	-.232	.657(**)	.454(**)	-.869(**)	.726(**)	.888(**)	-.049	.063	.482(**)
	Sig. (2-tailed)	.001	.139	.690	.000	.000	.058		.000	.315	.000	.078	.125	.000	.002	.000	.000	.000	.750	.680	.001
	N	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45
High Pulse Count	Pearson Correlation	-.403(**)	-.358(*)	-.141	.085	.808(**)	-.622(**)	.558(**)	1	-.809(**)	.955(**)	.336(*)	-.299(*)	.601(**)	.463(**)	-.837(**)	.952(**)	.628(**)	.466(**)	-.433(**)	.900(**)
	Sig. (2-tailed)	.006	.016	.354	.577	.000	.000	.000		.000	.000	.024	.046	.000	.001	.000	.000	.000	.001	.003	.000
	N	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45
High Pulse Duration	Pearson Correlation	.185	.245	.026	.285	-.657(**)	.647(**)	-.153	-.809(**)	1	-.744(**)	-.179	.163	-.450(**)	-.471(**)	.532(**)	-.740(**)	-.308(*)	-.414(**)	.298(*)	-.820(**)
	Sig. (2-tailed)	.224	.105	.865	.058	.000	.000	.315	.000		.000	.239	.286	.002	.001	.000	.000	.040	.005	.047	.000
	N	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45
High Pulse Range	Pearson Correlation	-.381(**)	-.253	-.006	.253	.756(**)	-.485(**)	.669(**)	.955(**)	-.744(**)	1	.242	-.188	.585(**)	.407(**)	-.889(**)	.961(**)	.781(**)	.286	-.195	.825(**)
	Sig. (2-tailed)	.010	.093	.968	.094	.000	.001	.000	.000	.000		.109	.216	.000	.006	.000	.000	.000	.056	.198	.000
	N	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45
Fall Rate	Pearson Correlation	-.941(**)	-.995(**)	-.162	-.164	.477(**)	-.693(**)	.266	.336(*)	-.179	.242	1	-.994(**)	.369(*)	.391(**)	-.296(*)	.340(*)	.035	.165	-.325(*)	.309(*)
	Sig. (2-tailed)	.000	.000	.288	.282	.001	.000	.078	.024	.239	.109		.000	.013	.008	.049	.022	.820	.278	.029	.039
	N	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45
Rise Rate	Pearson Correlation	.921(**)	.993(**)	.174	.202	-.455(**)	.693(**)	-.232	-.299(*)	.163	-.188	-.994(**)	1	-.376(*)	-.422(**)	.264	-.300(*)	.015	-.201	.369(*)	-.294(*)
	Sig. (2-tailed)	.000	.000	.253	.184	.002	.000	.125	.046	.286	.216	.000		.011	.004	.079	.045	.922	.185	.012	.050
	N	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45
Fall Count	Pearson Correlation	-.512(**)	-.366(*)	-.227	-.137	.762(**)	-.724(**)	.657(**)	.601(**)	-.450(**)	.585(**)	.369(*)	-.376(*)	1	.906(**)	-.710(**)	.690(**)	.574(**)	.087	-.245	.783(**)
	Sig. (2-	.000	.014	.134	.369	.000	.000	.000	.000	.002	.000	.013	.011		.000	.000	.000	.000	.570	.105	.000

Metric		7-Day Minimum Flow	1-Day Maximum Flow	Date Minimum Flow	Date Maximum Flow	Low Pulse. Count	Low Pulse Duration	Low Pulse. Range	High Pulse. Count	High Pulse Duration	High Pulse Range	Fall Rate	Rise Rate	Fall. Count	Rise. Count	Tqmean	R-B Index	Daily Max: Daily Mean Flow	%above2yr	OnsetFall	Reversals
	tailed)																				
	N	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45
Rise Count	Pearson Correlation	-.489(**)	-.413(**)	-.230	-.342(*)	.740(**)	-.762(**)	.454(**)	.463(**)	-.471(**)	.407(**)	.391(**)	-.422(**)	.906(**)	1	-.566(**)	.564(**)	.318(*)	.154	-.304(*)	.660(**)
	Sig. (2-tailed)	.001	.005	.128	.022	.000	.000	.002	.001	.001	.006	.008	.004	.000		.000	.000	.033	.312	.042	.000
	N	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45
T_{Qmean}	Pearson Correlation	.485(**)	.289	.010	-.393(**)	-.791(**)	.463(**)	-.869(**)	-.837(**)	.532(**)	-.889(**)	-.296(*)	.264	-.710(**)	-.566(**)	1	-.933(**)	-.869(**)	-.160	.150	-.765(**)
	Sig. (2-tailed)	.001	.055	.950	.008	.000	.001	.000	.000	.000	.000	.049	.079	.000	.000		.000	.000	.293	.324	.000
	N	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45
R-B Index	Pearson Correlation	-.475(**)	-.349(*)	-.018	.220	.892(**)	-.623(**)	.726(**)	.952(**)	-.740(**)	.961(**)	.340(*)	-.300(*)	.690(**)	.564(**)	-.933(**)	1	.781(**)	.310(*)	-.286	.874(**)
	Sig. (2-tailed)	.001	.019	.906	.147	.000	.000	.000	.000	.000	.000	.022	.045	.000	.000	.000		.000	.038	.057	.000
	N	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45
Daily Max:Daily Mean	Pearson Correlation	-.275	.000	.256	.645(**)	.583(**)	-.172	.888(**)	.628(**)	-.308(*)	.781(**)	.035	.015	.574(**)	.318(*)	-.869(**)	.781(**)	1	-.105	.152	.571(**)
	Sig. (2-tailed)	.067	.999	.090	.000	.000	.259	.000	.000	.040	.000	.820	.922	.000	.033	.000	.000		.491	.319	.000
	N	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45
% Time Above 2-year mean flow	Pearson Correlation	-.069	-.210	-.324(*)	-.150	.339(*)	-.286	-.049	.466(**)	-.414(**)	.286	.165	-.201	.087	.154	-.160	.310(*)	-.105	1	-.863(**)	.320(*)
	Sig. (2-tailed)	.654	.165	.030	.324	.023	.057	.750	.001	.005	.056	.278	.185	.570	.312	.293	.038	.491		.000	.032
	N	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45
Date of Onset of Fall Flows	Pearson Correlation	.182	.350(*)	.365(*)	.254	-.411(**)	.435(**)	.063	-.433(**)	.298(*)	-.195	-.325(*)	.369(*)	-.245	-.304(*)	.150	-.286	.152	-.863(**)	1	-.402(**)
	Sig. (2-tailed)	.232	.018	.014	.092	.005	.003	.680	.003	.047	.198	.029	.012	.105	.042	.324	.057	.319	.000		.006
	N	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45
Reversals	Pearson	-.377(*)	-.331(*)	-.130	-.135	.818(**)	-.763(**)	.482(**)	.900(**)	-.820(**)	.825(**)	.309(*)	-.294(*)	.783(**)	.660(**)	-.765(**)	.874(**)	.571(**)	.320(*)	-.402(**)	1

Metric		7-Day Minimum Flow	1-Day Maximum Flow	Date Minimum Flow	Date Maximum Flow	Low Pulse. Count	Low Pulse Duration	Low Pulse. Range	High Pulse. Count	High Pulse Duration	High Pulse Range	Fall Rate	Rise Rate	Fall. Count	Rise. Count	Tqmean	R-B Index	Daily Max: Daily Mean Flow	%above2yr	OnsetFall	Reversals
	Correlation																				
	Sig. (2-tailed)	.011	.026	.393	.376	.000	.000	.001	.000	.000	.000	.039	.050	.000	.000	.000	.000	.000	.032	.006	
	N	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45
Hourly Maximum Flow	Pearson Correlation	.(a)	.(a)	.(a)	.(a)	.(a)	.(a)	.(a)	.(a)	.(a)	.(a)	.(a)	.(a)	.(a)	.(a)	.(a)	.(a)	.(a)	.(a)	.(a)	.(a)
	Sig. (2-tailed)	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
	N	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

a Cannot be computed because at least one of the variables is constant.

Appendix A-2. Correlations Among Hydrological Metrics – HSPF Data

Metric		7daymin	1daymax	mindate	maxdate	Low Pulse Duration	Low Pulse Range	High Pulse Count	High Pulse Duration	High Pulse Range	FALL RATE	Rise Rate	Fall Count	Rise Count	TQmean	R-B Index	Hourly Maximum Flow	Daily Max:Mean Flow	% time flows are above 2-year mean flow	Normalized Effective Stream Power	Current 2-yr:Forested 10-yr Flow	Date of onset of fall flows	Minimum Baseflow	Runoff event count	Runoff Duration
7daymin	Pearson Correlation	1	.853(**)	.038	.119	.198(*)	-.224(**)	-.201(*)	.145	-.280(**)	-.709(**)	.792(**)	-.275(**)	-.267(**)	.351(**)	-.247(**)	.797(**)	-.234(**)	-.105	-.154	-.104	.088	1.000(**)	-.566(**)	.874(**)
	Sig. (2-tailed)		.000	.663	.170	.022	.009	.020	.096	.001	.000	.000	.001	.002	.000	.004	.000	.006	.226	.077	.231	.311	.000	.000	.000
	N	134	134	134	134	134	134	134	134	134	134	134	133	133	134	134	134	134	134	133	134	134	134	134	133
1daymax	Pearson Correlation	.853(**)	1	-.056	-.258(**)	.271(**)	.139	.079	-.146	-.072	-.913(**)	.992(**)	-.063	-.019	.003	.087	.985(**)	.138	-.286(**)	-.148	-.195(*)	-.095	.854(**)	-.585(**)	.937(**)
	Sig. (2-tailed)	.000		.520	.003	.002	.108	.363	.092	.406	.000	.000	.469	.824	.970	.317	.000	.113	.001	.089	.024	.276	.000	.000	.000
	N	134	134	134	134	134	134	134	134	134	134	134	133	133	134	134	134	134	134	133	134	134	134	134	133
mindate	Pearson Correlation	.038	-.056	1	.412(**)	.326(**)	-.401(**)	-.434(**)	.234(**)	-.586(**)	.295(**)	-.085	-.517(**)	-.524(**)	.396(**)	-.378(**)	-.149	-.080	-.302(**)	.002	-.650(**)	.853(**)	.039	.083	-.005
	Sig. (2-tailed)	.663	.520		.000	.000	.000	.000	.006	.000	.001	.327	.000	.000	.000	.000	.085	.357	.000	.979	.000	.000	.658	.339	.958
	N	134	134	134	134	134	134	134	134	134	134	134	133	133	134	134	134	134	134	133	134	134	134	134	133
maxdate	Pearson Correlation	.119	-.258(**)	.412(**)	1	.044	-.891(**)	-.503(**)	.424(**)	-.498(**)	.355(**)	-.305(**)	-.636(**)	-.531(**)	.711(**)	-.668(**)	-.327(**)	-.646(**)	.261(**)	-.034	-.004	.642(**)	.119	.241(**)	-.170
	Sig. (2-tailed)	.170	.003	.000		.611	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.002	.700	.960	.000	.170	.005	.051
	N	134	134	134	134	134	134	134	134	134	134	134	133	133	134	134	134	134	134	133	134	134	134	134	133
LPC	Pearson Correlation	-.291(**)	-.198(*)	-.434(**)	-.379(**)	-.847(**)	.476(**)	.618(**)	-.397(**)	.827(**)	.001	-.171(*)	.775(**)	.813(**)	-.545(**)	.659(**)	-.110	.465(**)	.279(**)	.419(**)	.557(**)	-.562(**)	-.294(**)	.538(**)	-.392(**)
	Sig. (2-tailed)	.001	.022	.000	.000	.000	.000	.000	.000	.000	.989	.048	.000	.000	.000	.000	.208	.000	.001	.000	.000	.000	.001	.000	.000
	N	134	134	134	134	134	134	134	134	134	134	134	133	133	134	134	134	134	134	133	134	134	134	134	133
LPD	Pearson Correlation	.198(*)	.271(**)	.326(**)	.044	1	-.087	-.344(**)	.209(*)	-.621(**)	-.148	.273(**)	-.626(**)	-.601(**)	.237(**)	-.309(**)	.218(*)	-.112	-.403(**)	-.290(**)	-.570(**)	.394(**)	.200(*)	-.554(**)	.436(**)

Metric		7daymin	1daymax	mindate	maxdate	Low Pulse Duration	Low Pulse Range	High Pulse Count	High Pulse Duration	High Pulse Range	FALL RATE	Rise Rate	Fall Count	Rise Count	TQmean	R-B Index	Hourly Maximum Flow	Daily Max:Mean Flow	% time flows are above 2-year mean flow	Normalized Effective Stream Power	Current 2-yr:Forested 10-yr Flow	Date of onset of fall flows	Minimum Baseflow	Runoff event count	Runoff Duration
	Sig. (2-tailed)	.022	.002	.000	.611		.317	.000	.015	.000	.087	.001	.000	.000	.006	.000	.011	.196	.000	.001	.000	.000	.021	.000	.000
	N	134	134	134	134	134	134	134	134	134	134	134	133	133	134	134	134	134	134	133	134	134	134	134	133
LPR	Pearson Correlation	-.224(**)	.139	-.401(**)	-.891(**)	-.087	1	.521(**)	-.346(**)	.506(**)	-.296(**)	.194(*)	.646(**)	.566(**)	-.800(**)	.733(**)	.220(*)	.699(**)	-.091	.128	.054	-.632(**)	-.224(**)	-.068	.055
	Sig. (2-tailed)	.009	.108	.000	.000	.317		.000	.000	.000	.001	.025	.000	.000	.000	.000	.010	.000	.298	.142	.534	.000	.009	.435	.529
	N	134	134	134	134	134	134	134	134	134	134	134	133	133	134	134	134	134	134	133	134	134	134	134	133
HPC	Pearson Correlation	-.201(*)	.079	-.434(**)	-.503(**)	-.344(**)	.521(**)	1	-.873(**)	.862(**)	-.326(**)	.166	.503(**)	.879(**)	-.840(**)	.939(**)	.189(*)	.790(**)	-.061	.303(**)	.455(**)	-.464(**)	-.200(*)	.319(**)	-.150
	Sig. (2-tailed)	.020	.363	.000	.000	.000	.000		.000	.000	.000	.055	.000	.000	.000	.000	.029	.000	.484	.000	.000	.000	.020	.000	.086
	N	134	134	134	134	134	134	134	134	134	134	134	133	133	134	134	134	134	134	133	134	134	134	134	133
HPD	Pearson Correlation	.145	-.146	.234(**)	.424(**)	.209(*)	-.346(**)	-.873(**)	1	-.684(**)	.297(**)	-.231(**)	-.466(**)	-.805(**)	.712(**)	-.790(**)	-.222(*)	-.750(**)	.264(**)	-.172(*)	-.212(*)	.237(**)	.143	-.272(**)	.093
	Sig. (2-tailed)	.096	.092	.006	.000	.015	.000	.000		.000	.000	.007	.000	.000	.000	.000	.010	.000	.002	.048	.014	.006	.099	.001	.289
	N	134	134	134	134	134	134	134	134	134	134	134	133	133	134	134	134	134	134	133	134	134	134	134	133
HPR	Pearson Correlation	-.280(**)	-.072	-.586(**)	-.498(**)	-.621(**)	.506(**)	.862(**)	-.684(**)	1	-.154	-.012	.739(**)	.909(**)	-.720(**)	.800(**)	.030	.584(**)	.114	.435(**)	.637(**)	-.681(**)	-.281(**)	.391(**)	-.269(**)
	Sig. (2-tailed)	.001	.406	.000	.000	.000	.000	.000	.000		.075	.895	.000	.000	.000	.000	.733	.000	.191	.000	.000	.000	.001	.000	.002
	N	134	134	134	134	134	134	134	134	134	134	134	133	133	134	134	134	134	134	133	134	134	134	134	133
FR	Pearson Correlation	-.709(**)	-.913(**)	.295(**)	.355(**)	-.148	-.296(**)	-.326(**)	.297(**)	-.154	1	-.935(**)	-.071	-.213(*)	.210(*)	-.306(**)	-.964(**)	-.239(**)	.020	.111	-.108	.305(**)	-.709(**)	.413(**)	-.791(**)
	Sig. (2-tailed)	.000	.000	.001	.000	.087	.001	.000	.000	.075		.000	.416	.014	.015	.000	.000	.005	.817	.203	.216	.000	.000	.000	.000
	N	134	134	134	134	134	134	134	134	134	134	134	133	133	134	134	134	134	134	133	134	134	134	134	133
RR	Pearson Correlation	.792(**)	.992(**)	-.085	-.305(**)	.273(**)	.194(*)	.166	-.231(**)	-.012	-.935(**)	1	-.028	.051	-.082	.168	.990(**)	.211(*)	-.294(**)	-.132	-.174(*)	-.121	.793(**)	-.547(**)	.909(**)
	Sig. (2-tailed)	.000	.000	.327	.000	.001	.025	.055	.007	.895	.000		.746	.557	.349	.052	.000	.015	.001	.131	.045	.162	.000	.000	.000

Metric		7daymin	1daymax	mindate	maxdate	Low Pulse Duration	Low Pulse Range	High Pulse Count	High Pulse Duration	High Pulse Range	FALL RATE	Rise Rate	Fall Count	Rise Count	TQmean	R-B Index	Hourly Maximum Flow	Daily Max:Mean Flow	% time flows are above 2-year mean flow	Normalized Effective Stream Power	Current 2-yr:Forested 10-yr Flow	Date of onset of fall flows	Minimum Baseflow	Runoff event count	Runoff Duration
	N	134	134	134	134	134	134	134	134	134	134	134	133	133	134	134	134	134	134	133	134	134	134	134	133
FC	Pearson Correlation	-.275(**)	-.063	-.517(**)	-.636(**)	-.626(**)	.646(**)	.503(**)	-.466(**)	.739(**)	-.071	-.028	1	.803(**)	-.616(**)	.584(**)	.007	.457(**)	.090	.302(**)	.359(**)	-.621(**)	-.277(**)	.268(**)	-.211(*)
	Sig. (2-tailed)	.001	.469	.000	.000	.000	.000	.000	.000	.000	.416	.746		.000	.000	.000	.938	.000	.302	.000	.000	.000	.001	.002	.015
	N	133	133	133	133	133	133	133	133	133	133	133	133	133	133	133	133	133	133	132	133	133	133	133	132
RC	Pearson Correlation	-.267(**)	-.019	-.524(**)	-.531(**)	-.601(**)	.566(**)	.879(**)	-.805(**)	.909(**)	-.213(*)	.051	.803(**)	1	-.786(**)	.868(**)	.082	.717(**)	.083	.318(**)	.496(**)	-.555(**)	-.268(**)	.440(**)	-.260(**)
	Sig. (2-tailed)	.002	.824	.000	.000	.000	.000	.000	.000	.000	.014	.557	.000		.000	.000	.346	.000	.340	.000	.000	.000	.002	.000	.003
	N	133	133	133	133	133	133	133	133	133	133	133	133	133	133	133	133	133	133	132	133	133	133	133	132
Tqmean	Pearson Correlation	.351(**)	.003	.396(**)	.711(**)	.237(**)	-.800(**)	-.840(**)	.712(**)	-.720(**)	.210(*)	-.082	-.616(**)	-.786(**)	1	-.925(**)	-.095	-.850(**)	.109	-.179(*)	-.240(**)	.520(**)	.350(**)	-.179(*)	.163
	Sig. (2-tailed)	.000	.970	.000	.000	.006	.000	.000	.000	.000	.015	.349	.000	.000		.000	.273	.000	.209	.040	.005	.000	.000	.038	.062
	N	134	134	134	134	134	134	134	134	134	134	134	133	133	134	134	134	134	134	133	134	134	134	134	133
Rbindex	Pearson Correlation	-.247(**)	.087	-.378(**)	-.668(**)	-.309(**)	.733(**)	.939(**)	-.790(**)	.800(**)	-.306(**)	.168	.584(**)	.868(**)	-.925(**)	1	.192(*)	.918(**)	-.129	.257(**)	.281(**)	-.502(**)	-.247(**)	.249(**)	-.124
	Sig. (2-tailed)	.004	.317	.000	.000	.000	.000	.000	.000	.000	.000	.052	.000	.000	.000		.027	.000	.138	.003	.001	.000	.004	.004	.156
	N	134	134	134	134	134	134	134	134	134	134	134	133	133	134	134	134	134	134	133	134	134	134	134	133
hourmax	Pearson Correlation	.797(**)	.985(**)	-.149	-.327(**)	.218(*)	.220(*)	.189(*)	-.222(*)	.030	-.964(**)	.990(**)	.007	.082	-.095	.192(*)	1	.203(*)	-.206(*)	-.131	-.091	-.188(*)	.797(**)	-.527(**)	.893(**)
	Sig. (2-tailed)	.000	.000	.085	.000	.011	.010	.029	.010	.733	.000	.000	.938	.346	.273	.027		.019	.017	.133	.298	.030	.000	.000	.000
	N	134	134	134	134	134	134	134	134	134	134	134	133	133	134	134	134	134	134	133	134	134	134	134	133
dayQmax.mean	Pearson Correlation	-.234(**)	.138	-.080	-.646(**)	-.112	.699(**)	.790(**)	-.750(**)	.584(**)	-.239(**)	.211(*)	.457(**)	.717(**)	-.850(**)	.918(**)	.203(*)	1	-.381(**)	.167	-.086	-.269(**)	-.234(**)	.156	-.051
	Sig. (2-tailed)	.006	.113	.357	.000	.196	.000	.000	.000	.000	.005	.015	.000	.000	.000	.000	.019		.000	.055	.323	.002	.007	.072	.563
	N	134	134	134	134	134	134	134	134	134	134	134	133	133	134	134	134	134	134	133	134	134	134	134	133

Metric		7daymin	1daymax	mindate	maxdate	Low Pulse Duration	Low Pulse Range	High Pulse Count	High Pulse Duration	High Pulse Range	FALL RATE	Rise Rate	Fall Count	Rise Count	TQmean	R-B Index	Hourly Maximum Flow	Daily Max:Mean Flow	% time flows are above 2-year mean flow	Normalized Effective Stream Power	Current 2-yr:Forested 10-yr Flow	Date of onset of fall flows	Minimum Baseflow	Runoff event count	Runoff Duration
%above2yr	Pearson Correlation	-.105	-.286(**)	-.302(**)	.261(**)	-.403(**)	-.091	-.061	.264(**)	.114	.020	-.294(**)	.090	.083	.109	-.129	-.206(*)	-.381(**)	1	-.054	.660(**)	-.281(**)	-.109	.374(**)	-.299(**)
	Sig. (2-tailed)	.226	.001	.000	.002	.000	.298	.484	.002	.191	.817	.001	.302	.340	.209	.138	.017	.000		.535	.000	.001	.209	.000	.000
	N	134	134	134	134	134	134	134	134	134	134	134	133	133	134	134	134	134	134	133	134	134	134	134	133
Power	Pearson Correlation	-.154	-.148	.002	-.034	-.290(**)	.128	.303(**)	-.172(*)	.435(**)	.111	-.132	.302(**)	.318(**)	-.179(*)	.257(**)	-.131	.167	-.054	1	.315(**)	-.021	-.154	.226(**)	-.190(*)
	Sig. (2-tailed)	.077	.089	.979	.700	.001	.142	.000	.048	.000	.203	.131	.000	.000	.040	.003	.133	.055	.535		.000	.813	.078	.009	.029
	N	133	133	133	133	133	133	133	133	133	133	133	132	132	133	133	133	133	133	133	133	133	133	133	132
Q2_Q10	Pearson Correlation	-.104	-.195(*)	-.650(**)	-.004	-.570(**)	.054	.455(**)	-.212(*)	.637(**)	-.108	-.174(*)	.359(**)	.496(**)	-.240(**)	.281(**)	-.091	-.086	.660(**)	.315(**)	1	-.573(**)	-.105	.359(**)	-.283(**)
	Sig. (2-tailed)	.231	.024	.000	.960	.000	.534	.000	.014	.000	.216	.045	.000	.000	.005	.001	.298	.323	.000	.000		.000	.227	.000	.001
	N	134	134	134	134	134	134	134	134	134	134	134	133	133	134	134	134	134	134	133	134	134	134	134	133
onsetfall	Pearson Correlation	.088	-.095	.853(**)	.642(**)	.394(**)	-.632(**)	-.464(**)	.237(**)	-.681(**)	.305(**)	-.121	-.621(**)	-.555(**)	.520(**)	-.502(**)	-.188(*)	-.269(**)	-.281(**)	-.021	-.573(**)	1	.088	.055	-.021
	Sig. (2-tailed)	.311	.276	.000	.000	.000	.000	.000	.006	.000	.000	.162	.000	.000	.000	.000	.030	.002	.001	.813	.000		.309	.529	.808
	N	134	134	134	134	134	134	134	134	134	134	134	133	133	134	134	134	134	134	133	134	134	134	134	133
baseminflow	Pearson Correlation	1.000(**)	.854(**)	.039	.119	.200(*)	-.224(**)	-.200(*)	.143	-.281(**)	-.709(**)	.793(**)	-.277(**)	-.268(**)	.350(**)	-.247(**)	.797(**)	-.234(**)	-.109	-.154	-.105	.088	1	-.565(**)	.875(**)
	Sig. (2-tailed)	.000	.000	.658	.170	.021	.009	.020	.099	.001	.000	.000	.001	.002	.000	.004	.000	.007	.209	.078	.227	.309		.000	.000
	N	134	134	134	134	134	134	134	134	134	134	134	133	133	134	134	134	134	134	133	134	134	134	134	133
runoffcount	Pearson Correlation	-.566(**)	-.585(**)	.083	.241(**)	-.554(**)	-.068	.319(**)	-.272(**)	.391(**)	.413(**)	-.547(**)	.268(**)	.440(**)	-.179(*)	.249(**)	-.527(**)	.156	.374(**)	.226(**)	.359(**)	.055	-.565(**)	1	-.793(**)
	Sig. (2-tailed)	.000	.000	.339	.005	.000	.435	.000	.001	.000	.000	.000	.002	.000	.038	.004	.000	.072	.000	.009	.000	.529	.000		.000
	N	134	134	134	134	134	134	134	134	134	134	134	133	133	134	134	134	134	134	133	134	134	134	134	133
runoffdur	Pearson Correlation	.874(**)	.937(**)	-.005	-.170	.436(**)	.055	-.150	.093	-.269(**)	-.791(**)	.909(**)	-.211(*)	-.260(**)	.163	-.124	.893(**)	-.051	-.299(**)	-.190(*)	-.283(**)	-.021	.875(**)	-.793(**)	1

Metric		7daymin	1daymax	mindate	maxdate	Low Pulse Duration	Low Pulse Range	High Pulse Count	High Pulse Duration	High Pulse Range	FALL RATE	Rise Rate	Fall Count	Rise Count	TQmean	R-B Index	Hourly Maximum Flow	Daily Max:Mean Flow	% time flows are above 2-year mean flow	Normalized Effective Stream Power	Current 2-yr:Forested 10-yr Flow	Date of onset of fall flows	Minimum Baseflow	Runoff event count	Runoff Duration
	Sig. (2-tailed)	.000	.000	.958	.051	.000	.529	.086	.289	.002	.000	.000	.015	.003	.062	.156	.000	.563	.000	.029	.001	.808	.000	.000	
	N	133	133	133	133	133	133	133	133	133	133	133	132	132	133	133	133	133	133	132	133	133	133	133	133
runoffdurmax	Pearson Correlation	.918(**)	.847(**)	.050	.023	.353(**)	-.148	-.246(**)	.189(*)	-.384(**)	-.692(**)	.798(**)	-.355(**)	-.369(**)	.311(**)	-.258(**)	.799(**)	-.203(*)	-.213(*)	-.227(**)	-.227(**)	.086	.919(**)	-.728(**)	.926(**)
	Sig. (2-tailed)	.000	.000	.566	.796	.000	.089	.004	.028	.000	.000	.000	.000	.000	.000	.003	.000	.019	.013	.008	.008	.325	.000	.000	.000
	N	134	134	134	134	134	134	134	134	134	134	134	133	133	134	134	134	134	134	133	134	134	134	134	133
reversals	Pearson Correlation	-.179(*)	-.173	-.485(**)	-.075	-.782(**)	.026	.616(**)	-.571(**)	.733(**)	-.048	-.142	.487(**)	.730(**)	-.304(**)	.482(**)	-.084	.259(**)	.317(**)	.166	.698(**)	-.457(**)	-.180(*)	.554(**)	-.400(**)
	Sig. (2-tailed)	.043	.051	.000	.401	.000	.771	.000	.000	.000	.586	.108	.000	.000	.000	.000	.344	.003	.000	.061	.000	.000	.041	.000	.000
	N	129	129	129	129	129	129	129	129	129	129	129	128	128	129	129	129	129	129	128	129	129	129	129	128
maxhour.meanday	Pearson Correlation	-.359(**)	-.164	.076	-.135	-.436(**)	.271(**)	.625(**)	-.602(**)	.576(**)	.041	-.106	.414(**)	.681(**)	-.502(**)	.641(**)	-.097	.670(**)	-.001	.265(**)	.092	-.038	-.358(**)	.690(**)	-.390(**)
	Sig. (2-tailed)	.000	.059	.380	.119	.000	.002	.000	.000	.000	.635	.225	.000	.000	.000	.000	.266	.000	.994	.002	.288	.663	.000	.000	.000
	N	134	134	134	134	134	134	134	134	134	134	134	133	133	134	134	134	134	134	133	134	134	134	134	133

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).